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Soft Handover Parameter Optimisation for DS-CDMA Downlink Design

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September 1995

A thesis submitted to the University of Bristol in accordance with the requirements for the degree of Doctor of Philosophy in the Faculty of Engineering, Department of Electrical and Electronic Engineering.

To Karen

Abstract

This thesis focusses on the development of a network planning tool to investigate the optimisation of handover parameters for a future generation Direct Sequence-Code Division Multiple Access (DS-CDMA) downlink. The work concentrates on the comparison of the quality-of-service attainable from a system incorporating the more traditional technique of Hard Handover, with that of the relatively new macroscopic diversity concept know as Soft Handover.

Handover between adjacent base stations is investigated using both simulated and practical results to estimate the Quality-of-Service (QoS) offered by each handover technique. The simulations used a Monte-Carlo approach to study the effects of the environmental propagation statistics, as well as the handover threshold on the system capacity. For example, it was found that *"in contrast to hard handover, the capacity of a soft handover system could be increased by using a larger threshold window, achieving an optimum capacity with a threshold value in the range 4dB to 6dB."*

Practical measurements were made in a variety of third generation cellular environments. Received Pilot/Channel information was obtained using a purpose-built wideband DS-CDMA Fast Fourier Transform (FFT), dual-channel sounder system, operating at around 1.8GHz. Analysis of this data and optimisation of the handover techniques was performed using a generic handover algorithm (GHA) developed specifically for this purpose. The algorithm proposed adopts a system of timers and hysteresis levels set relative to the received pilot signal strengths to select the operational base station. Depending on the handover strategy to be employed, the handover parameters can be altered and the projected signalling channel improvements monitored, to provide an analysis of the handover scenario environment and to establish the relative QoS trade-offs which can be achieved.

Finally the core achievements of this work are summarised and conclusions are drawn from the studies performed, concerning future planning for soft handover's incorporation into a third generation cellular downlink.

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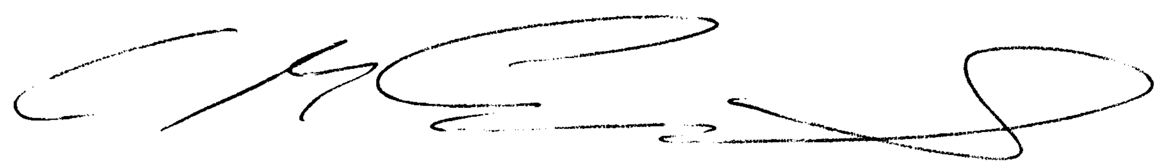
Author's Declaration

Unless otherwise acknowledged, the content of this thesis is the original and sole work of the author. No portion of the work in this thesis has been submitted by the author in support of an application for any other degree or qualification, at this or any other university or institute of learning. The views expressed in this thesis are those of the author, and not necessarily those of the University of Bristol.



Christopher Martin Simmonds

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List of Abbreviations

ACTS	Advanced Communications Technologies and Services
ADC	Analogue to Digital Convertor
AF	Audio Frequency
AM	Amplitude-Modulation
ATDMA	Advanced Time Division Multiple Access project
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPF	BandPass Filter
BPSK	Binary Phase-Shift Keying
BS	Base Station
BSC	Base Station Controller
BSS	Base Station Subsystem
BTS	Base Tranceiver System
cdf	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CIR	Complex Impulse Response
CODIT	COde DIvision Testbed
COST	european COoperation in the field of Scientific Technical research
CT2	Cordless Telephone system 2
DAC	Digital to Analogue Convertor

DAMPS	Digital Advanced Mobile Phone Service
dB	Decibel
dBm	Decibels relative to 1 milliwatt
DCS1800	Digital Cellular System 1800
DECT	Digital European Cordless Telephone
DS-CDMA	Direct Sequence Code Division Multiple Access
DSP	Digital Signal Processing
DTI	Department of Trade and Industry
EPSRC	Engineering and Physical Sciences Research Council
ETS	European Telecommunication Standards Institute
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FH-CDMA	Frequency Hopping Code Division Multiple Access
FM	Frequency Modulation
GHA	Generic Handover Algorithm
GSM	Global System for Mobile communications (formerly Groupe Spécial Mobile)
H/o	Handover
IBC	Integrated Broadband Communications
IF	Intermediate Frequency
IMT-2000	International Mobile Telecommunications system 2000
IQ	In-phase and Quadrature data
ISDN	Integrated Services Digital Network
ISI	Inter-Symbol Interference
ITU	International Telecommunications Union
LOS	Line-Of-Sight

LPF	Low-Pass Filter
MAHO	Mobile-Assisted HandOver
MAVT	Mobile Audio-Visual Terminal project
MBS	Mobile Broadband Services
MCHO	Mobile-Controlled HandOver
MMI	Man-Machine Interface
MONET	MObile NETwork project
MSC	Mobile Switching Centre
m-sequence	Maximal length pseudo-random data sequence
MSK	Minimum Shift Keying
NCHO	Network-Controlled HandOver
OMC	Operation and Maintenance Centre
pdf	Probability Density Function
PCS	Personal Communications Services
PHS	Personal Handyphone System
PLATON	PLAnning TOols for mobile radio Networks
PMR	Private Mobile Radio
PSTN	Public Switched Telephone Network
QoS	Quality-of-Service
QPSK	Quadrature Phase-Shift Keying
RACE	Research and development of Advanced Communications technologies in Europe
RMS	Root Mean Square
RTD	Research and Technological Development
RF	Radio Frequency
RTD	Research and Technological Development

SINR	Signal-to-Interference-Noise Ratio
SERC	Science and Engineering Research Council
SNR	Signal-to-Noise Ratio
TACS	Total Access Communications System
TDMA	Time Division Multiple Access
TETRA	Trans-European Trunked Radio System
TH-CDMA	Time Hopping CDMA
TIA	Telecommunications Industry Association
UMTS	Universal Mobile Telecommunication System
WARC	World Administrative Radio Conference
WG	Working Group

List of Symbols

a_i	Signal amplitude weighting in signal branch i
B	Bandwidth
C/I	Carrier-to-Interference Ratio
D	Duty Cycle
E_b	Energy per bit
f	Frequency
G	Number of sectors per cell
G_p	Processing Gain
K	Frequency Reuse Factor
L	Pseudo-noise code length
log	Logarithm base 10
N_{BS}	Number of base stations
N_{Its}	Number of iterations
N_{Tiers}	Number of cell tiers
N_{Users}	Number of users
N_T	Total Noise Power
N_0	Noise Power Spectral Density
$\bar{n}_i^2$	Noise Power for branch i
P_e	Probability of error
r_{i_j}	Distance of user i from a base station j

R_b	Bit Rate
R_c	Chip Rate
R_{user}	Maximum Radius of user distribution
R_{hex}	Radius of a hexagonal coverage area
S	Signal Power
t_{Add}	Soft Handover Add Timer
t_c	Chip period
t_{Delay}	Average Delay Spread
t_{Drop}	Soft Handover Drop Timer
t_{Rms}	RMS Delay Spread
α	Pathloss exponent
β	Proportion of power allocated to users
Δ_{Thresh}	Handover Threshold
η	Bandwidth Efficiency
γ	Signal-to-noise ratio
Φ_i	Power fraction transmitted to mobile user i
σ_{log}	Shadowing standard deviation
ξ	Shadowing exponent

List of Publications

S. A. Allpress, M. A. Beach, G. Martin and C. M. Simmonds, "An Investigation of RAKE Receiver Operation in an Urban Environment for Various Spreading Bandwidth Allocations", *Proceedings of the* 42^{nd} *International Conference on Vehicular Technology,* (IEEE), Denver, Colorado, May 1992

M. A. Beach, S. Chard, J. C. S. Cheung, C. M. Simmonds and J. P. McGeehan, "Soft Handoff Demonstration", *RACE PLATON Work Package G3.8*, March 1993

C. M. Simmonds, D. Yang and M. A. Beach, "Network Planning Aspects of DS-CDMA", *Proceedings of the International Conference on Antennas and Propagation,* (IEE), Edinburgh, UK, April 1993

C. M. Simmonds and M. A. Beach, "Network Planning Aspects of DS-CDMA with Particular Emphasis on Soft Handoff", *Proceedings of the* 43^{rd} *International Conference on Vehicular Technology,* (IEEE), Secaucus, New Jersey, USA, May 1993

S. C. Swales, J. C. S. Cheung, C. M. Simmonds, M. A. Beach and J. P. McGeehan, "Handoff Requirements for a Third Generation DS-CDMA Air Interface", *Proceedings of Mobility in Support of Personal Communications Colloquium* (IEE), London, UK, June 1993

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C. M. Simmonds and M. A. Beach , "Macroscopic Diversity Handover Analysis in a Microcellular Environment" *Proceedings of the* 2^{nd} *International Workshop on Mobile Multimedia Communications* (IEEE) Bristol, UK, April 1995

Chapter 1

Background

> ***"In the not too distant future, the telecommunications networks will be capable of instantly transporting and processing voice traffic, text and images between any locations, be they homes, offices or businesses, thanks to digitalisation techniques and electronic processing of information. These networks will therefore constitute the nervous system of the economy, and more generally of tomorrow's society"*** - Commission of the European Communities, White Paper, *"Growth, Competitiveness, Employment - The Challenges and Ways Forward into the 21st Century"*. [1]

1.1 Current Wireless Mobile Communications Systems

This century has seen the development of public wireline networks that allow reliable and affordable communication of voice and low-rate data around the globe. There has also been the development of specialised wired networks optimised for the purposes of local high-speed data communications. The goal of wireless communications is to provide a multiplicity of services regardless of location and mobility. Cellular and cordless telephony, both of which have gained widespread user acceptance during the last ten years, have begun this process but as yet do not provide truly wireless communications. Current cellular systems can offer only voice and low-speed data within limited areas covered by base stations [2].

The most basic handset can only operate within a short range of the base station (typically 50-100m) which connects to the public switched telephone network (PSTN). With the advent of digital cordless telephony, cordless "systems" with enhanced functionality have been developed which can support higher data rates and more sophisticated applications such as wireless private exchanges (PBXs) and public-access Telepoint systems, such systems include the Cordless Telephone systems (CT2), the Digital European Cordless Telephone (DECT) and in Japan, the Personal Handyphone System (PHS).

The Global System for Mobile communications (GSM) provides the standard for digital cellular communications systems, allowing mass public services operating in the wide area. In addition to digital transmission, GSM offers many other advanced service features such as ISDN compatibility and pan-European roaming, although more recently it has been taken up by countries outside Europe [3].

Another common system available is Private Mobile Radio (PMR), of which there are several hundred licencees in the UK alone. Characterised by a simple air-interface with minimal layer separation, PMR systems operate as very low capacity cellular systems, with communications links usually limited to a single, or closed user group.

In addition to terrestrial based communications systems are satellite systems e.g. Inmarsat (INternational MAritime SATellite), which was set up to provide maritime safety and distress communications in addition to providing the main trunk services that support links between the major operators [4].

The presence and relative youth of some of these systems are likely to have a strong influence on the development of future wireless systems, due to the amount of investment in hardware and technology some operators have made in these currently operational systems.

1.2 Future Generation System Planning

The following sections discuss the major projects which have or are currently investigating the system planning aspects for the future generation of cellular communications.

1.2.1 RACE and ACTS

The Research and Development of Advanced Communications technologies in Europe or the RACE programme, was first conceived in 1984. The aim of the project was to gain a common vision of the future communications infrastructure for Europe, through collaboration between various European research institutes. Although more recently, companies from the USA and Japan with substantial Research and Technological Development (RTD) resources in Europe have been encouraged to participate.

The work structure of the RACE Programme was broken down into three phases. Phase I focussed on the system engineering, specifications and key technologies available; Phase II the integration and prototyping of new services and applications; and Phase III is to continue beyond the RACE programme, consisting of user-driven experimentation.

The first two phases were implemented by a series of related but autonomous projects and are due to come to a conclusion in 1995. These projects included:

- Project MObile NETwork (MONET) [5], the main objectives of which are to specify and study the feasibility of the mobility functions, protocols and network architectures which will enable the UMTS to become an integrated part of the infrastructure for third generation fixed telecommunications.
- Advanced TDMA Mobile Access (ATDMA) [6], which is investigating the feasibility of using a TDMA technique (Section 2.6.2) as the air interface standard for UMTS.
- COde DIvision Testbed (CODIT) [7], hopes to establish the feasibility of CDMA (Section 2.6.3) for the air interface technique. Achievements are to be by the design, construction and validation through simulation, as well as field trials.
- PLAnning TOol for mobile radio Networks (PLATON) [8] [9], which was to produce a planning tool based on a set of tele-services, their traffic distribution and geographical terrain databases, to give the best cell configurations according to grade of services to be offered, available spectrum for that service and cost. This work was to include studies of cell architectures, quality of service requirements, propagation characteristics, soft handover variables and mobility issues. However, work on this project has since ceased.

The ACTS programme (Advanced Communications Technologies and Services) represents the European Commission's major effort to support Phase III of RTD support of trials which are preparing the ground for a Europe-wide, internationally competitive, information infrastructure or *'infostructure'*. These projects focus on the continuity of the RACE objectives with a view to demonstrating how the achievements of this work can be built upon and used to further the European contribution to Integrated Broadband Communications (IBC). Figure 1.1 shows how the ACTS and RACE phases fit into the implementation of IBC in Europe.

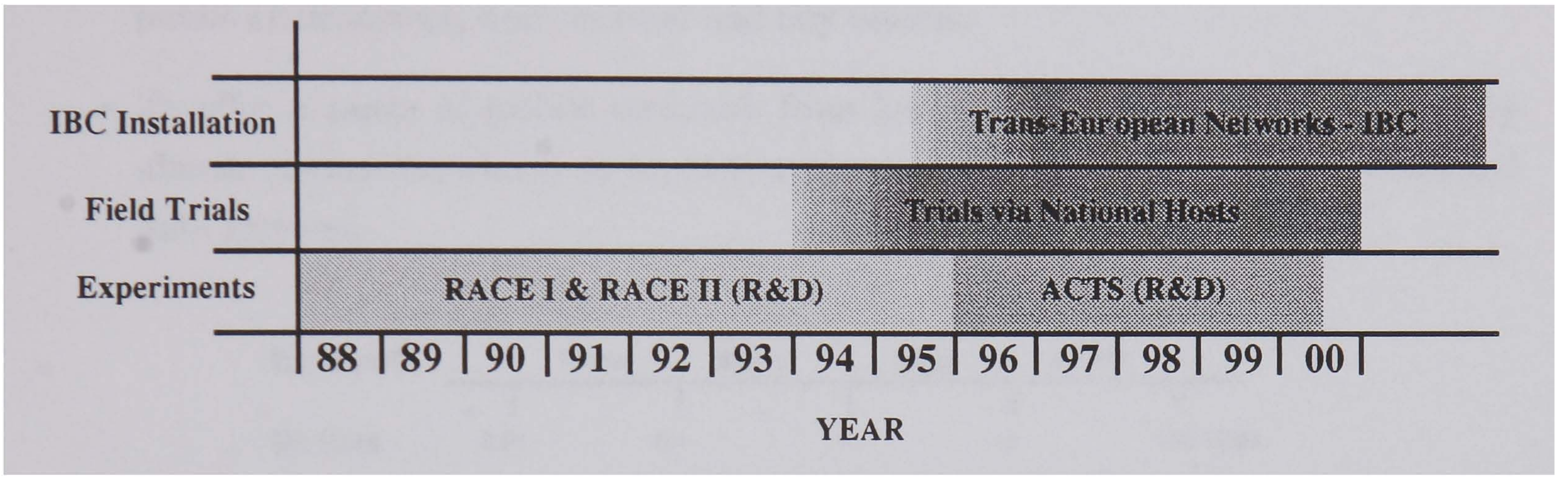

Figure 1.1: IBC Implementation Phases

Proposed projects under ACTS include:

- Software Tools for the Optimisation of Resources in Mobile Systems (STORMS), the main objective of the project consists of the definition, implementation and validation of a software tool to be used for design and planning of the UMTS network.
- Future Radio Wideband Multiple Access Systems (FRAMES), whose overall objectives are to define a specification of a UMTS multiple access air interface.

1.2.2 UMTS

The Universal Mobile Telecommunication System (UMTS) is currently being developed in Europe. It was allocated the frequency band 1700-2690MHz by the World Administrative Radio Conference 1992 (WARC'92) [10]. UMTS-related activities are led by research conducted within the RACE II programme and standardisation activities within the European Telecommunication Standards Institute (ETSI). UMTS is to be a realisation of a new generation of mobile communications technology in which *"personal services will be based on a combination of fixed and wireless/mobile services to form a seamless end-to-end service for the user"* [11].

Some of the requirements of UMTS are :

- To support existing mobile services and fixed telecommunications services up to 2MBits/s (although mobile service applications in the range of 2-100MBits/s are being considered under RACE Mobile's Mobile Broadband System (MBS) which will operate at around 60GHz). The proposed services are outlined in Figure 1.2
- To support unique mobile services such as navigation, vehicle location and road traffic information services, both in rural areas and city centres.
- To allow UMTS terminals to be used anywhere, in the home, the office and in the public environment, both in rural and city centres.
- To offer a range of mobile terminals from low cost pocket telephones (for use by almost anyone anywhere) to sophisticated terminals, providing advanced video and data services.

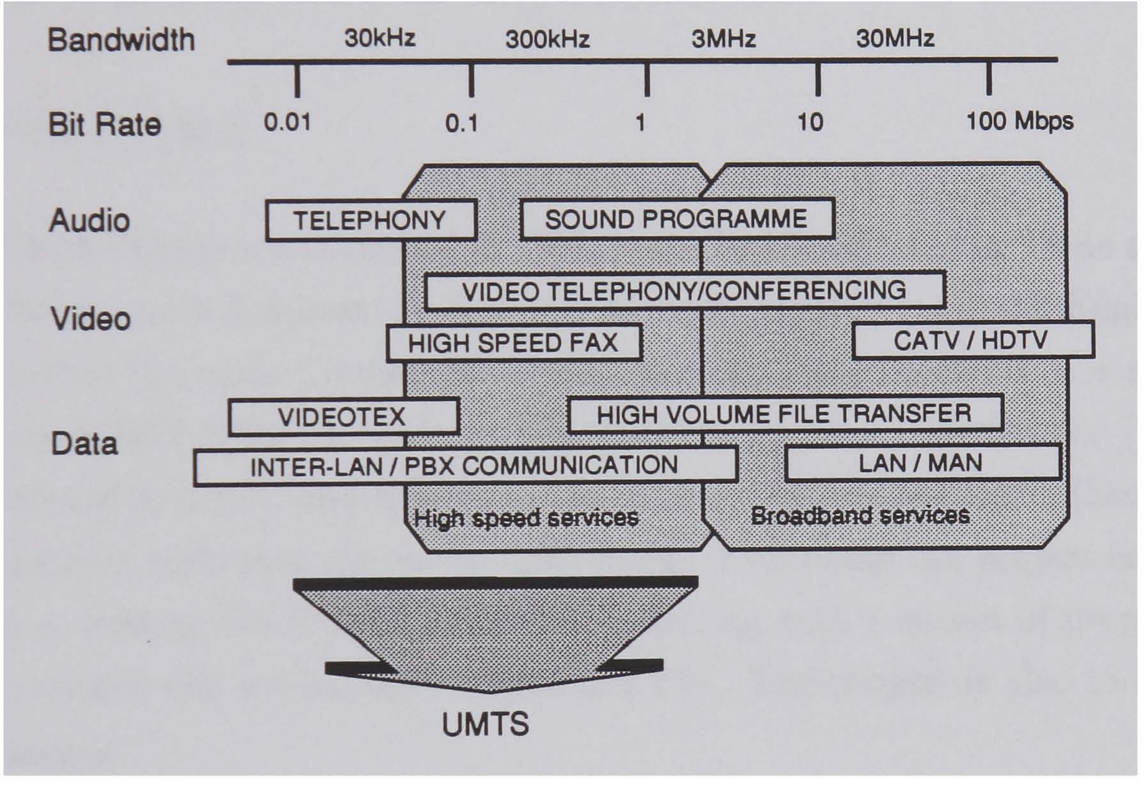

Figure 1.2: Bandwidth Requirements for UMTS

1.2.3 IMT-2000

An effort similar to UMTS is underway in the ITU (International Telecommunications Union) under the name of FPLMTS (Future Public Land Mobile Telecommunications System) recently renamed to IMT-2000 (International Mobile Telecommunication 2000). It is expected that UMTS and IMT-2000 will be compatible, so as to provide roaming on a global scale.

1.2.4 COST 231

European Co-operation in the Field of Scientific Technical Research (COST) is a framework and a forum for any member country to use to further scientific research. The COST 231 project is a follow-up on the project COST 207 [12], involving 24 European "COST states" in 1992, although recent events in Europe have somewhat changed the list members, if only by name [13]. COST 231 deals with Land Mobile Radio and Personal Communications and was set up in April 1989 to support both the cell planning of GSM and more advanced studies into the field of mobile and personal communications using access techniques such as TDMA, DS-CDMA and FH-CDMA. There are three Working Groups (WG's) within COST 231: WG1 (systems), WG2 (propagation) and WG3 (broadband systems). It is expected to contribute to ETSI Sub Technical Committee 5 "Special Mobile Group" (STC SMG 5) to carry out standardisation work related to UMTS. COST 231 is due to finish in April 1996, although its successor has not yet been decided.

1.2.5 LINK CDMA

The LINK CDMA project was started in 1992, with the Department of Trade and Industry (DTI) and Science and Engineering Research Council (SERC) (now the Engineering and Physical Sciences Research Council (EPSRC)) funding the project. It is a collaborative effort between AT&T Network Systems UK, Hewlett Packard Laboratories (Bristol) and the Universities of Bradford and Bristol, to evaluate the use of DS-CDMA (Section 2.6.3.3) as the air interface technique for use in UMTS [14]. Eventually the project is expected to demonstrate a working DS-CDMA radio link operating with a subset of proposed UMTS services in a mixed cell environment (Section 2.2.2). The project is also to evaluate the following features :

- Impact of a wideband system's operation (spreading at 8.192MChips/s).
- Optimisation of the air interface parameters, e.g. closed-loop power control, synchronisation and handover.
- Coherent Rake reception at both mobile and base stations.
- Prediction of the system capacity through measurement and artificial cell loading.
- To improve the general understanding of DS-CDMA operation and the problems facing system and network designers in its implementation.

1.3 The Form of the Thesis

The remainder of this thesis addresses the planning needs for UMTS, with particular emphasis on the implementation of the macroscopic diversity technique know as *"soft handover"*, into a third generation cellular radio system. To achieve this end, the chapters have been structured as follows :

Chapter 2 gives consideration to the various planning aspects of a future generation cellular system with respect to user mobility. These include aspects of cell design, such as the proposed mixed cell scenario and the basic network infrastructure. The idea of handover is introduced and the basic protocols discussed. The final section gives consideration to the various types of multiple access air interface under consideration for use in a future system. Direct Sequence Code Division Multiple Access (DS-CDMA) is chosen as the air interface technique which is used in subsequent chapters and analysis.

Chapter 3 introduces the concept of system Quality-of-Service (QoS) and discusses the relevant measures for a DS-CDMA, cellular system. Further to this concept is added an analytical study of a cellular system, to assess the capacity gains possible through the use of soft handover rather than hard handover. The study also provides analysis into the sensitivity of the capacity to variations in environmental and handover threshold parameters.

Chapter 4 describes the propagation study measurements used in the practical assessment of the soft handover scheme. The Fast Fourier Transform (FFT) dual-channel sounding system is described in detail and a discussion given of its operational performance. This chapter also includes the generic handover algorithm used in the field trial data analysis.

Chapter 5 contains the results of the field trials in four cellular handover scenarios. The channel sounder propagation statistics are presented for each environment, along with the optimised handover parameters obtained from the generic handover algorithm.

Chapter 6 provides a review of the work presented in this thesis. In this section conclusions are drawn from the results obtained and recommendations are made towards the optimised implementation of soft handover in a third generation cellular system. The final section in this chapter makes suggestions as to the future development of the planning tools used to investigate soft handover and provide a more rigourous assessment of the QoS such a system would have to offer.

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Chapter 2

Handover Planning Aspects of Future Cellular Systems

The problems of planning a wireless network may be formalised as follows: ***"GIVEN the subscriber density and statistical behaviour, geographical characteristics and available bandwidth as input data, MINIMISE cost of radio and network infrastructure WITH RESPECT TO radio coverage, cell size, frequency plan, and network quality, SUBJECT TO quality of service constraints."*** - B. Jabbari et al., IEEE Communications Magazine, *"Network Issues for Wireless Communications."* [1]

2.1 Introduction

This chapter gives consideration to the various major aspects of planning a cellular radio system, with reference to handover between base stations. The first two sections are concerned with the actual network configuration and infrastructure, after which the idea and need for handover is introduced as a requirement to support user mobility within networks and discussed on a system level. Finally, the relevant air interface techniques currently under consideration for use in the third generation mobile communications system are presented, with a particular emphasis on the spread spectrum technique known as Direct Sequence Code Division Multiple Access or DS-CDMA.

2.2 Cellular Evolution

The early mobile communications systems could only provide users with coverage in one of two ways: either point-to-point communications between users, which restricted the distance that those users could be apart, or distance from a central communications server, or base station, which would allow connection to another user within range of that base station, or even connection to the hard-wired public telephone system. Coverage by such systems was confined to a single region and highly restricted the total number of users that could be supported.

2.2.1 The Cellular Concept

The first *"cellular"* systems were developed only relatively recently by Bell Laboratories in the 1970's [2]. The early cellular systems divided up the coverage areas required by a mobile phone system into a series of smaller, lower power coverage areas or *"cells"*. The main advantage behind this, other than reducing the power requirements of the individual base stations, was to allow the re-allocation of the finite number of channels allocated for that system, to other cells far enough away that the use of these channels would not result in co-channel interference. This gave rise to the principle of channel, or spectrum *"re-use"* (Section 3.2.3) whereby the same frequencies or channels could be used in a distant cell such that they caused little or no interference to the first cell's users. The re-use of the channels within the same system allows the operator to effectively increase the number of channels available and hence increase the system capacity [3].

This idea readily caught on amongst the mobile system operators and has allowed mobile telephony to spread worldwide. However, due to the unprecedented growth of interest in the mobile telephony area, many of the initial operators became saturated and had to limit or stop future growth. Had the market interest been more accurately gauged at an earlier stage, then no doubt the systems would have been better supported by the technologies of the day.

Today, new spectrum is being allocated to allow for the expansion of this cellular concept[1] From studies undertaken, the current mid-range estimates of the use of mobile communications in Europe alone, are in the region of 40 million users by the year 2000 and 80 million by the year 2010 [5]. Similarly, for the US, in the 1970's the anticipated cellular subscribership was estimated to be only 300,000 in 1994, whereas in actual fact by mid-1994 the figure was over 19 million [4], which was an increase of 48% on the previous year.

2.2.2 Third Generation Mixed Cell Environments

Current generation systems use a simple network of overlapping cells to provide adequate coverage for their users. This is usually symbolised by a tessellation of hexagons. This conventional cellular pattern dictated that base station antennas were simply mounted in prominent positions and high transmit powers used to provide adequate coverage of the area. However, it is now known that this strategy is not optimal for providing for a high user capacity in dense urban areas [6]. In addition to this, to accommodate the range of services and coverage required for the next generation systems (Section 1.2.2), a new cellular network structure has been proposed. This structure consists of three cell types: main coverage provided by large macro- or umbrella cells, enhanced by the deployment of smaller microcells and picocells within them (Figure 2.1).

- **Macrocells**. These are expected to provide coverage of at least 1km in urban areas, greater regions in rural areas. This would enable the network to support higher speed users e.g. motorway, fast vehicular users, with a reduction in the number of handovers required between cells per average call length. The maximum speed that could be supported would depend on the actual cell sizes and the signalling overhead of the system.

- **Microcells**. These are likely to give *in-street* coverage. Microcellular base station antennas would be mounted within the street level, possibly at the height of lamp posts. As a result, rather than circular (or hexagonal) coverage areas, as is usually depicted, the cell shapes are governed by the street configurations, with line-of-sight (LOS) being the dominant propagation means. They are expected to provide coverage of up to 200m, depending on the street layout and could be used to provide coverage for areas which cannot be reached by the macrocells, or to serve subscribers on foot

[1] Additionally, with the relaxation of Government and Military spectrum allocations, at the end of the cold war [4], new spectrum, especially in the US, has been made available for commercial use.

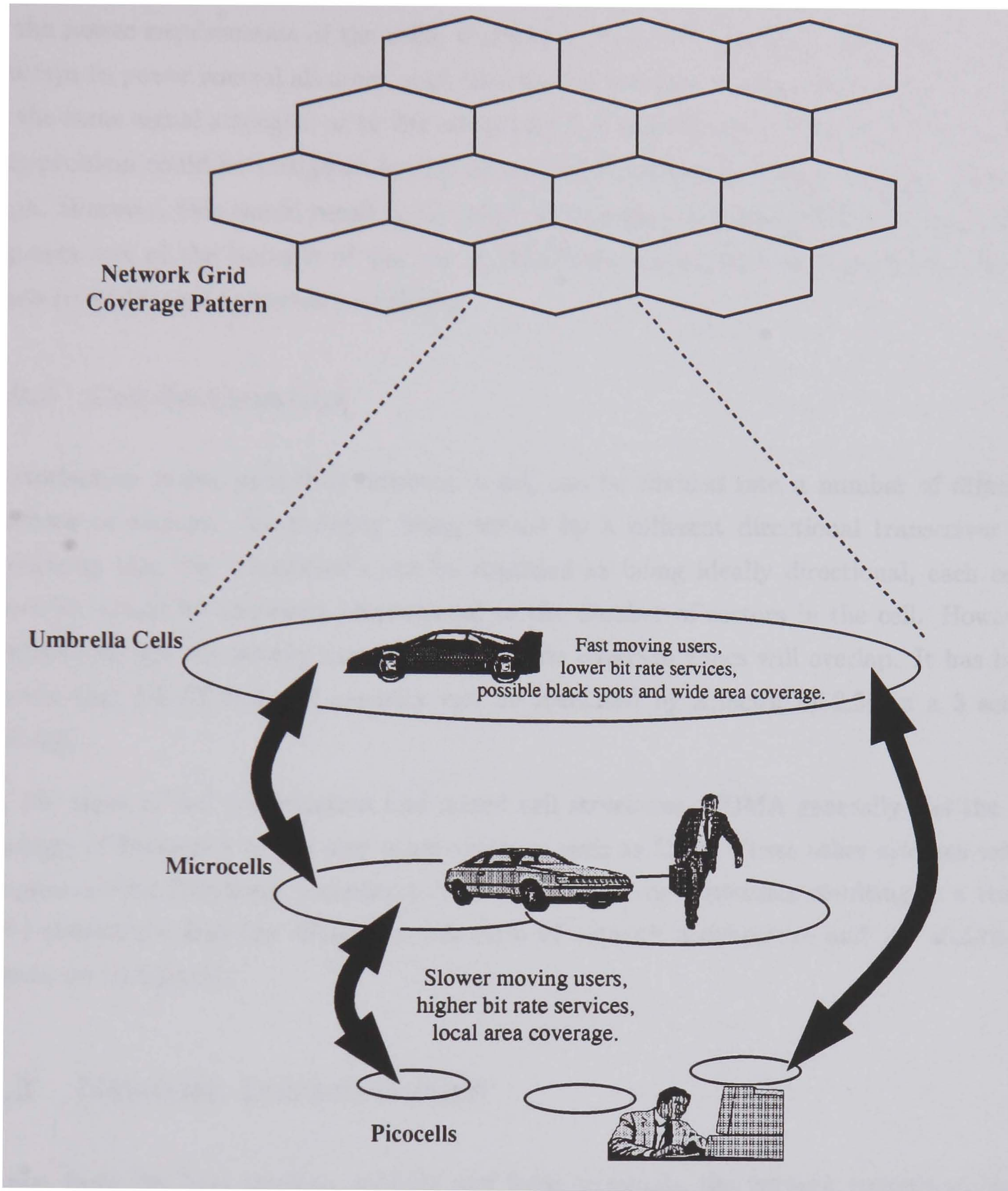

Figure 2.1: Envisioned Third Generation Mixed Cell Concept

with lower power terminals. Consideration is also being given to connecting microcells in clusters, linked to a parent macrocell base station by fibre-optic links to simplify microcellular base station units [7].

- **Picocells**. These are used to describe indoor cells with coverage regions typically of a single room. Ranges are expected to be up to 50m.

However, with this mixed cell structure come additional problems for a CDMA system. The near-far effects (Section 3.2.2.2) are likely to cause additional power problems at the edges of cells of different sizes (or types), due to the difference in the order of magnitudes of the power requirements of the cells. Current strategies to overcome this problem are to attempt to power control all users, such that the transmitted signals are effectively received at the same signal strength, or to use an optimal linear detection system [8]. Alternatively, this problem could be mitigated by the allocation of different frequency bands to each cell type. However, this would result in the need for frequency planning of the systems, which removes one of the benefits of the use of DS-CDMA (mentioned in Section 2.6.3.3) and leads to additional hardware complexity.

2.2.3 Cell Sectorisation

Sectorisation is the procedure whereby a cell can be divided into a number of different sections or sectors. Each sector being served by a different directional transceiver [9]. Assuming that the transceivers can be regarded as being ideally directional, each cell's capacity would be increased proportional to the number of sectors in the cell. However, transceivers are not totally directional and these coverage zones will overlap. It has been shown that DS-CDMA cell capacity can be increased by a factor of 2.55 in a 3 sector cell [10].

In the cases of cell sectorisation and mixed cell structures, CDMA generally has the advantage of frequency re-use over other systems, such as GSM. These other systems would require careful frequency planning to implement such cell structures resulting in a trade-off between the benefits offered by this style of network architecture and the additional hardware complexity.

2.3 Network Infrastructure

Apart from the base stations, mobiles and fixed terminals, the network consists of many other system elements which are essential to its operation.

Each cellular coverage area will be served by a base station, whether it is a low power transceiver for a picocell, or a high power transceiver covering an umbrella cell. Each requires connection to the fixed network to allow calls and other services to be set-up, managed and terminated or "torn-down".

Using the network infrastructure used in the GSM system as an example [11] and with reference to Figure 2.2, each operational Mobile Station (MS) must be in contact with a base station unit or Base Transceiver System (BTS). The BTS is little more than a radio transmission and reception device. Each BTS provides coverage to a number of MS's currently within its coverage area. Several BTS's can be connected to a Base Station Controller (BSC), which is in charge of all the radio interface management through remote command of the BTS's and MS's. Together the BSC and BTS's make the Base Station Subsystem or BSS. BSS's are in turn connected to a Mobile Switching Centre or MSC, which permits the connection of a MS to other areas of the network, as well as the external network e.g. PSTN, ISDN, etc. and co-ordinates the call set-up and tear-down processes. As such, the MSC is the unit that will establish the routing of calls through the network for the handover process.

MSC's are also connected in turn to higher level operating units such as the Operation and Maintenance Centre (OMC), which controls the network management as a whole; the Home Location Register, Visitor Location Register, etc., only deal with identification and validation of a user on the network and therefore will not be discussed further.

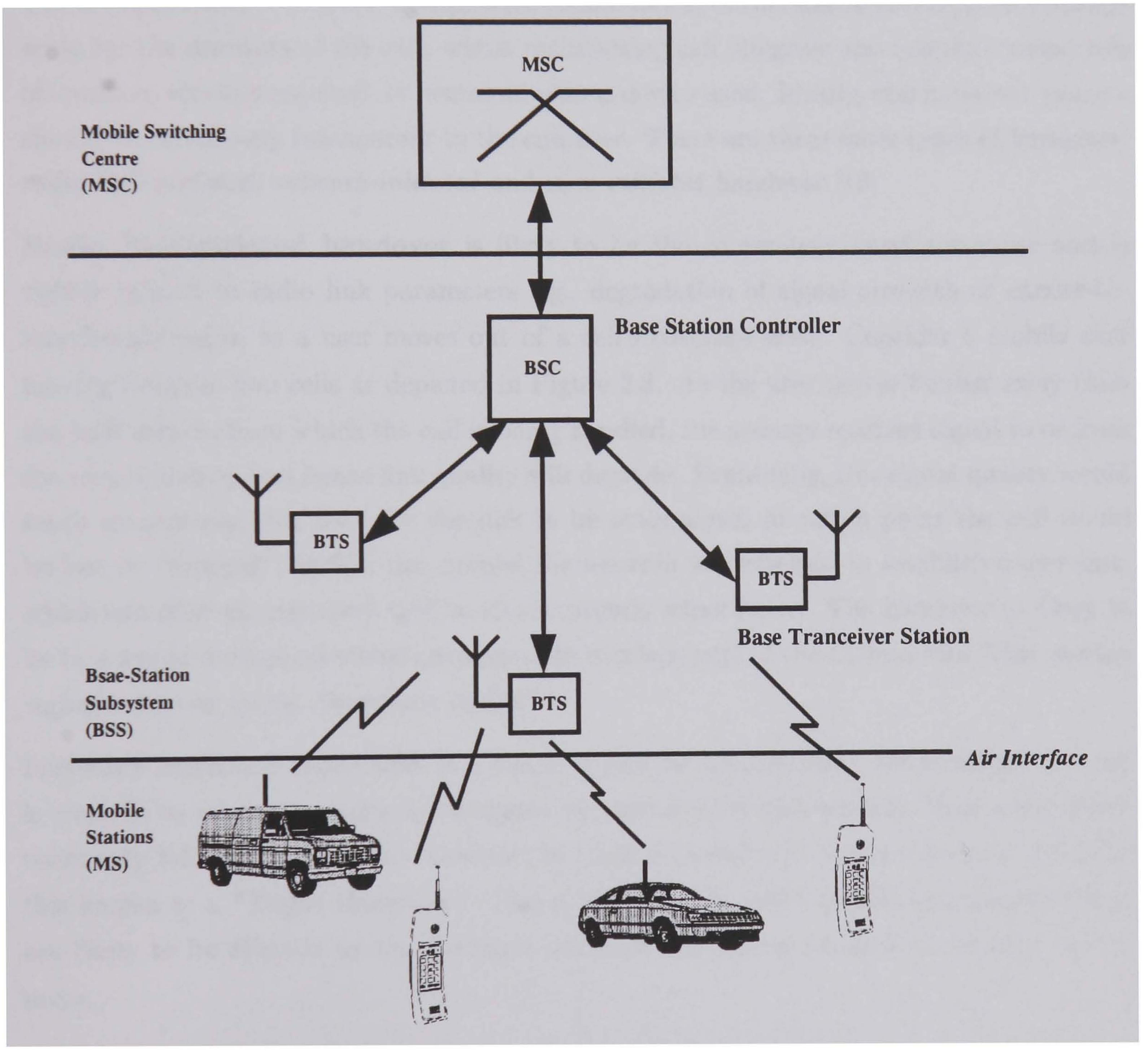

Figure 2.2: Basic Cellular Network Infrastructure

2.4 Handover in a Cellular System

Fundamentally, the handover process allows users to *roam* between coverage areas during the duration of a call. Without handover, users would be confined to a particular cell or region.

The handover process is where a user's call, currently being handled by one base station, is passed over to another channel within the same cell (intracellular handover) or to another base station (intercellular handover), which is deemed by the network to be better suited to handle the call at that point.

The main criterion is to allow a subscriber total freedom of movement between cell coverage areas for the duration of the call, whilst maintaining call integrity and quality, irrespective of location, services required, or communications device used. Ideally, this handover process should be completely transparent to the end user. There are three basic types of handover: *radio link-initiated*, *network-initiated* and *user-initiated* handover [12]

Radio link-initiated handover is likely to be the commonest handover cause and is tightly related to radio link parameters e.g. degradation of signal strength or carrier-to-interference ratio, as a user moves out of a cell's coverage area. Consider a mobile user moving between two cells as depicted in Figure 2.3. As the user moves further away from the base station from which the call is being handled, the average received signal to or from the user will drop and hence link quality will degrade. Eventually, this signal quality would reach an unacceptable level for the link to be maintained, at which point the call would be lost or *"dropped"*. Before this occurs, the network will attempt to establish a new link, which can offer an improved QoS to that currently experienced. The handover is likely to be to a neighbouring cell whose coverage area overlaps part of the current cell. This overlap region is known as the *"handover region"*.

Network-initiated handover, is a result of system management. For example, if a cell is close to its operating capacity of users and surrounding cells are not, then some of the users may be handed-off, where possible, to these adjacent cells to ease the load. In GSM this known as a *"Traffic Handover"*. This is also true of a cell's traffic requirements which are likely to be affected by the demands made on the variety of services required by the users.

In a **user-initiated handover**, there are also considerations to be made as to the demands the user is likely to make on the network. For example, considering users moving onto a motorway in an urban area, it may be more viable to hand those users over to a larger motorway coverage cell (long thin cells), if they exist, than to allow them to remain in the smaller, urban coverage cells. These urban cells may also provide coverage over the same

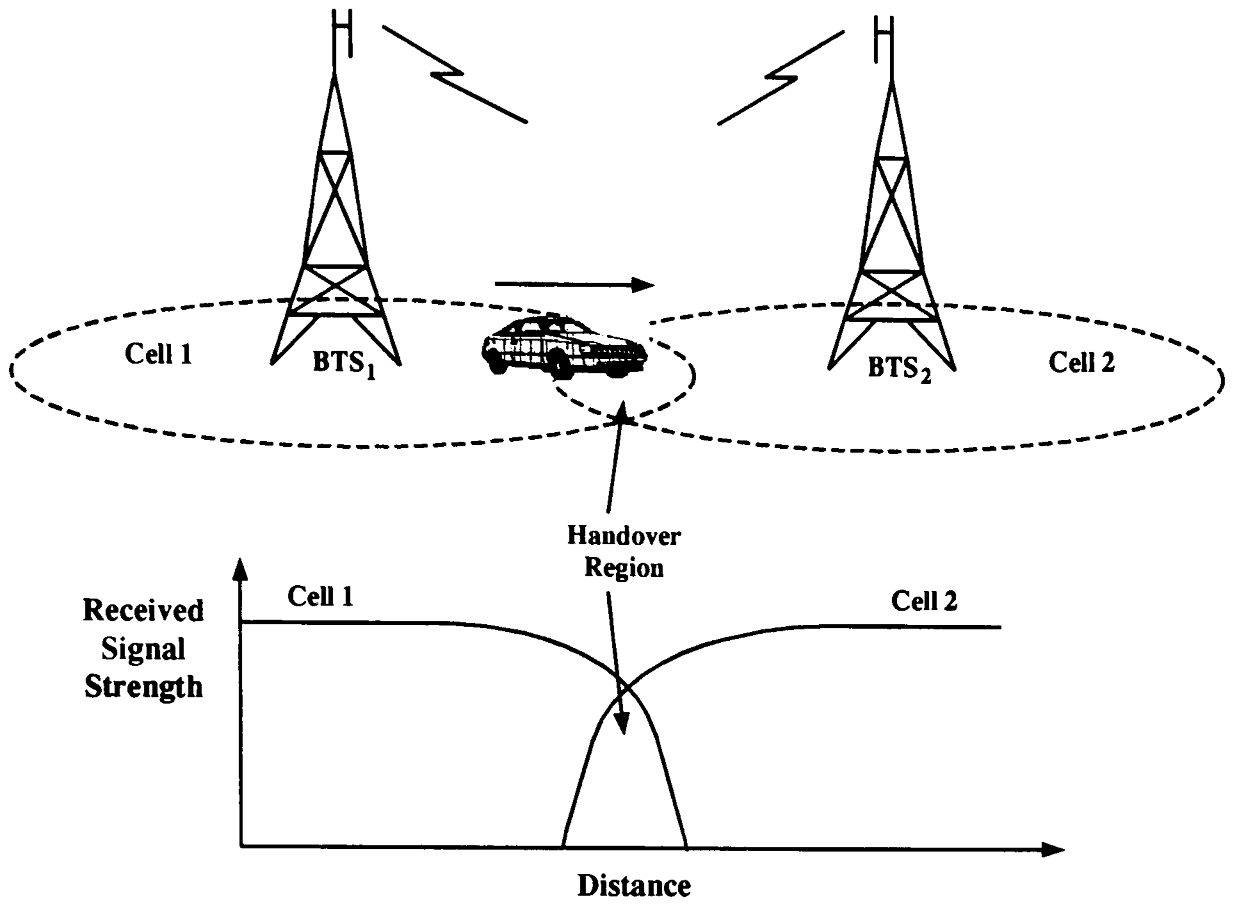

Figure 2.3: Mobile User Crossing Between Cells

part of the motorway, but would result in each user making a rapid succession of handovers due to their speed and the cell's size, which in turn would greatly increase the signalling required and unnecessarily load the network.

Also, handover has to be carefully considered from the network point of view. There is little point in handing a user over to another base station if the improved signal quality provided by that link is only transient. One example of this would be unnecessarily handing over to an out-of-sight base station at street crossings [13].

2.4.1 Hard Handover

Hard Handover is the *traditional* handover technique which has been adopted by most cellular systems to date. Although the full intricacies of the handover process (new channel allocation, user identification, network signalling overhead) are dependent on the system operator, the basic procedure is the same.

Figure 2.4 outlines the handover principle as far as establishing a new link in through the network. Hard Handover is known as a *"break-before-make"* system because once the handover process starts, the old link with the mobile station is terminated before the new link to the mobile is established. In this way there is no network redundancy on the communications link, as only one base station at a time handles the call. This does however leave the mobile user open to losing the link at the point of handover if any stage of the new link setup fails e.g. through a lost or corrupted handover message. At this point the

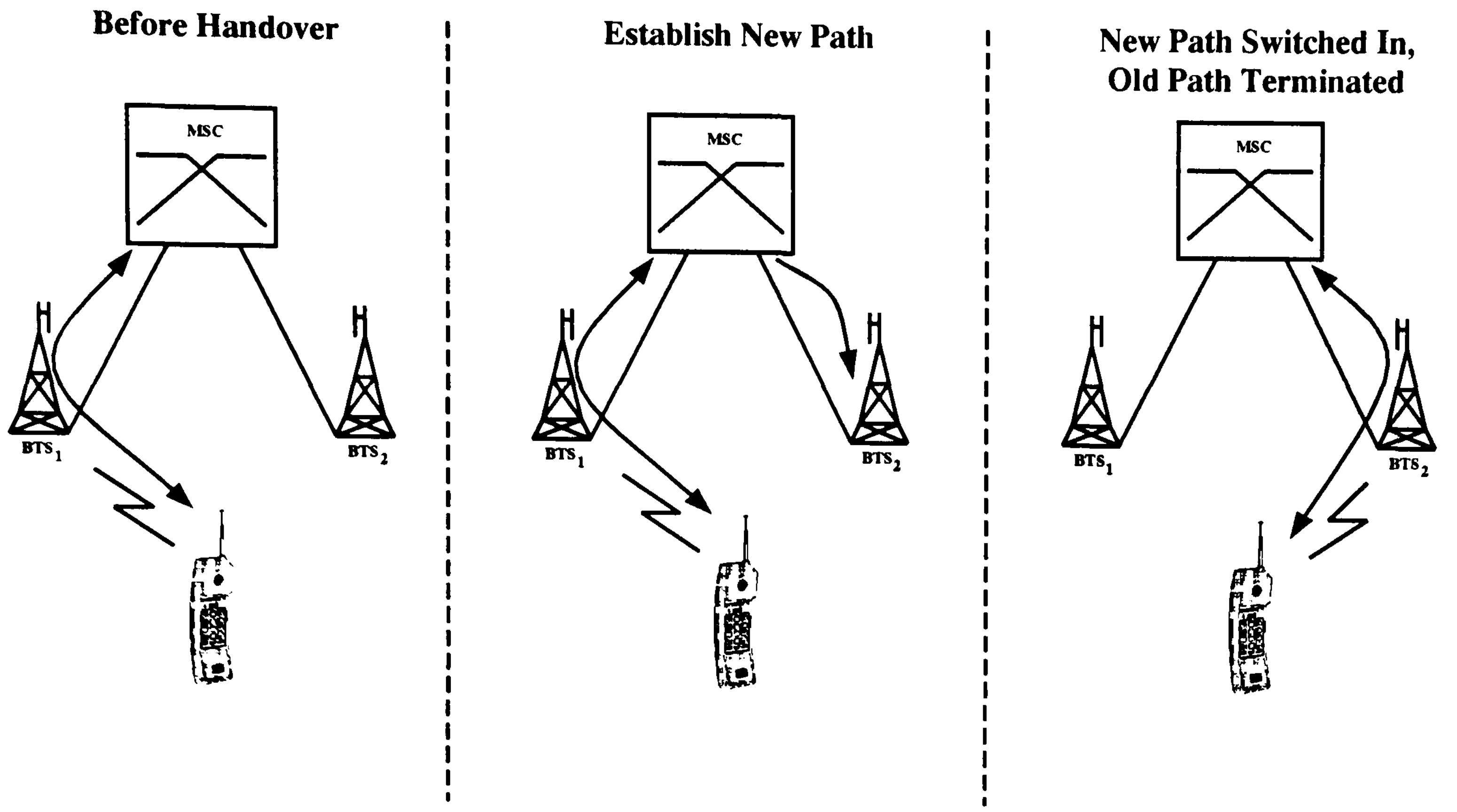

Figure 2.4: New Signal Path Establishment in Hard Handover

network would then have to attempt to re-establish communications with the mobile, if this is at all possible.

2.4.2 Soft Handover

Soft handover is a form of macroscopic diversity [14], which relies on the principle of diversity combining of independent (or uncorrelated) signal paths to provide an enhanced communications link with respect to signal strength. Hence this technique can reduce the required E_b/N_0 for a given error rate. It has been shown that macroscopic diversity can reduce the link margin required for 99% reliability by as much as 10dB [15].

This is a handover technique whereby transmissions from the same mobile station are received at different base stations and then used to establish the best communications link for the uplink: i.e the transmitted signal information is sent to the MSC by both of the BTS's along with a signal quality weighting. The MSC decides which communications path provides the higher quality link, based on this weighting and switches the paths appropriately (cell diversity) to the rest of the network. In a DS-CDMA system, it would also be possible for the undecoded or even undemodulated signals to be sent to the MSC to allow the utilisation of a better diversity combining process than switching to be used [16].

In the case of the downlink, both BTS's transmit the same information to the mobile unit, which can then combine the signals to provide an overall enhanced communications link. The techniques used for combining such signals are discussed in more detail in Section 4.3.

Soft handover differs from hard handover in one important aspect. Soft handover allows the mobile user to establish a link with a new base station *before* terminating the connection with the old base station. Figure 2.5 demonstrates this process. In this way, connection between the network and the mobile station should never be jeopardised during the handover process. The region over which the mobile station is connected to more than one base station, is termed the *"soft handover region"*.

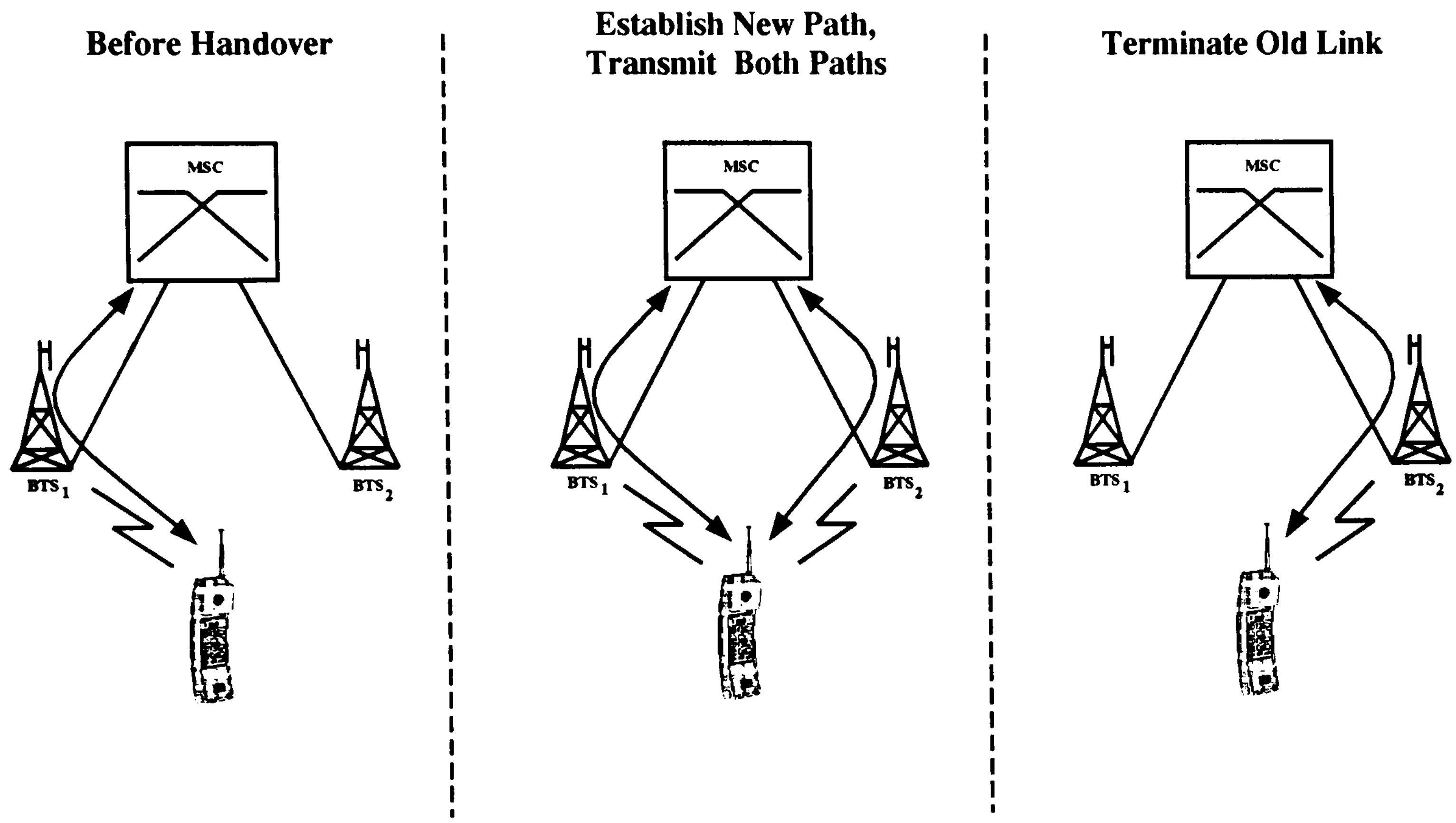

Figure 2.5: New Signal Path Establishment in Soft Handover

Intra-cellular handover is possible using the soft handover technique, where cell sectorisation is used. In this case the mobile handover operation, sometimes termed *"softer"* handover, is no different to inter-cellular soft handover. However, at the base station, the signals are diversity combined to improve signal-to-noise ratio performance.

One of the obvious short-falls of the soft handover process is that it contributes redundancy to the network loading. The same call must be carried by more than one base station whilst a user remains in handover. If the process is not carefully managed by the network, then it could quite easily result in a reduction in the overall network capacity.

2.4.3 Seamless Handover

A further handover scheme exists, which is part-way between hard and soft handover, known as *seamless* handover and is currently exploited by the DECT system. In this scheme, as the mobile user reaches the handover point, a new path is established to the new base station, whilst maintaining the old link. The call information is now transmitted by the mobile on both paths using separate carriers, although the active path remains through the old link. At handover, the the new path is switched in the network and the old path and links are released. In this manner there is no break in communications, as in the hard handover scheme, but the possible benefits of path diversity are not fully exploited, as in soft handover. However, this does allow the mobile to monitor the quality of the new link and not have to rely on measurement reports on the radio interface to make a decision on the point of handover. Section 2.5 gives a more detailed discussion on handover protocols and the role of the mobile or base station in the handover decision process.

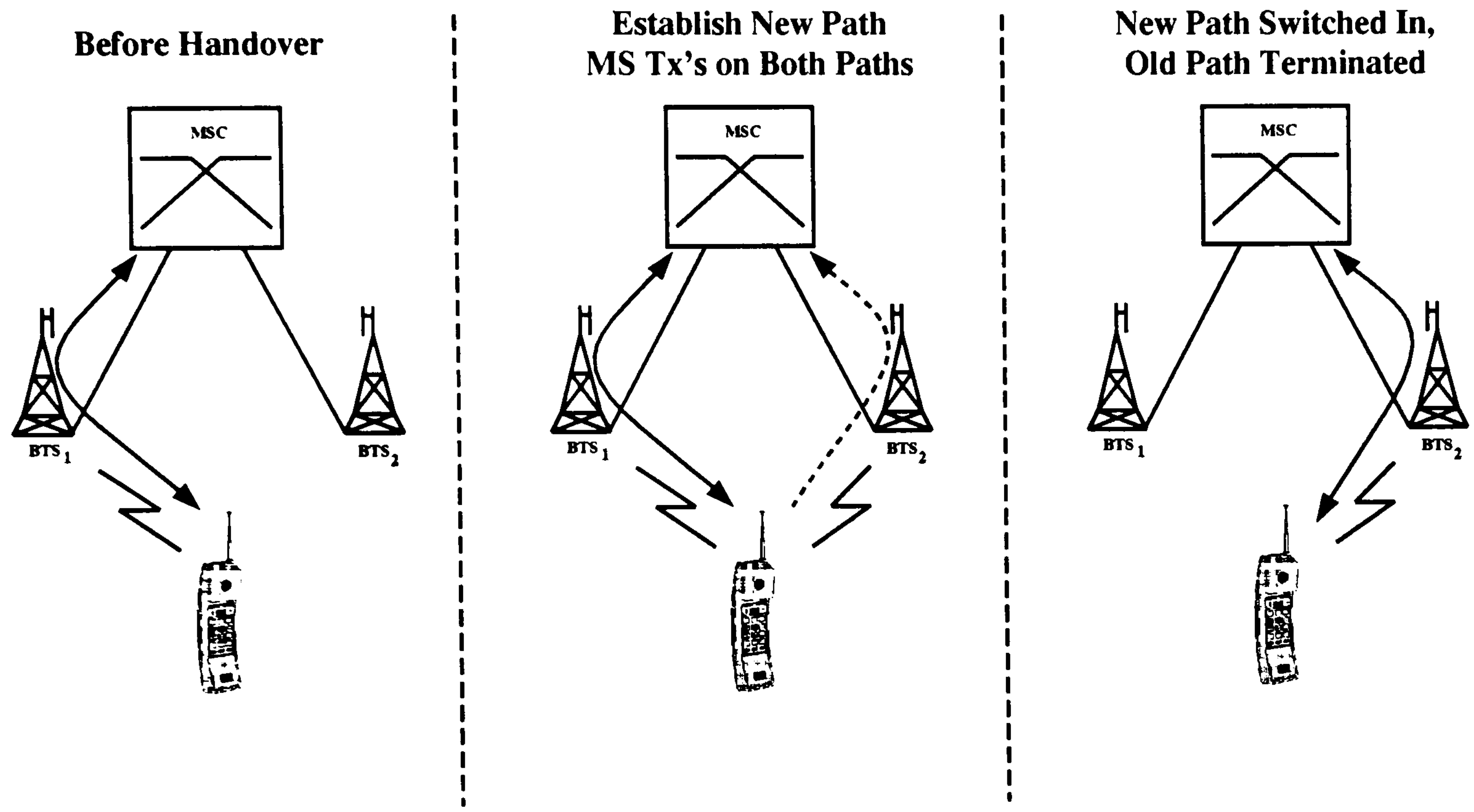

Figure 2.6: New Signal Path Establishment in Seamless Handover

2.5 Basic Handover Protocols

Irrespective of the reasons behind a handover, be it degrading signal quality, cell capacity, etc., a decision must be made within the system that a handover is to take place. This decision can be made by the fixed network, the mobile or a combination of the two, depending on the scheme adopted. Currently there exist three basic handover protocols.

- Firstly, in a **Network-Controlled Handover** (NCHO) such as that used by analogue cellular systems e.g. AMPS, TACS, NMT, etc., the mobile is entirely passive. Each base station monitors the received signal quality of any mobiles and the decision to handover is made within the network at the Mobile Switching Centre (MSC). Handover can take seconds and the monitoring of channel quality is infrequent.
- Secondly, digital cellular systems such as GSM in Europe, or TIA in the US, use a process known as **Mobile-Assisted Handover** (MAHO), whereby the mobile transmits a quality measurement of the downlink twice a second. Thereby allowing the base station to make estimates of the both up and downlink quality. The final handover decision is still made within the network and handover time is of the order of one second.
- Finally, in the European Digital Cordless Cellular system or DECT, the quality of the current link is measured by both the mobile and the base station, the base station transmitting its measurement report down to the mobile. The mobile also monitors other available channels and makes the final handover decision. This is known as a **Mobile-Controlled Handover** (MCHO) and the handover time is about 100ms.

As can be seen, differences exist not only in handover times but link quality monitoring and reporting. In the case of a MAHO, missed or incorrectly received handover request signals could be result in delaying the handover process or even losing the call. As a result, careful consideration must be given to the handover protocol to be adopted for any future system as to its appropriateness for the cellular environment and services which are offered.

2.6 Multiple Access Air Interface Techniques

Research into an appropriate air interface technique for the future generation communications system has been an area of considerable interest [17] [18], [19], producing three main contenders for the role: Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA).

The requirements for a third generation system far exceed those of the current second generation wireless networks and can only be satisfied by employing a suitable air interface. Should only one air interface technique be chosen, it must first meet a number of stringent criteria as follows:

- Capacity - The air interface must be able to support the required level of user traffic.
- Hardware - Provision must be made for low cost, compact and power efficient user terminals.
- Flexibility - To provide support for a wide range of services with varying bit rates.
- Quality of Service (QoS) - Be able to provide a high performance and low cost service.

However, all these criteria must be considered together, since they are all interdependent, e.g. one proposed scheme may be able to support a very high level of user traffic, but only at the expense of the hardware complexity, cost, etc., possibly prohibiting its selection for the air interface standard. Although it is now considered that a single air interface technique may not be able to provide the full range of services at the quality required and a flexible air interface may be needed which can exploit the benefits each can offer [19].

2.6.1 FDMA

The technique of Frequency Division Multiple Access (FDMA) simply divides up the available spectrum into channels. Each user can be assigned the use of one channel for communications, which is available to that user all the time. For example, if there are K possible users and an available bandwidth B, then each user could be assigned a portion B_u Hz, such that:

$$B_u = \frac{B}{K} = f_b\text{Hz}. \tag{2.1}$$

Figure 2.7 shows the channel arrangement.

However, for frequency division duplex (FDD) communications, (simultaneous two-way), then two bands will be required, one for transmission and one for reception. FDMA can

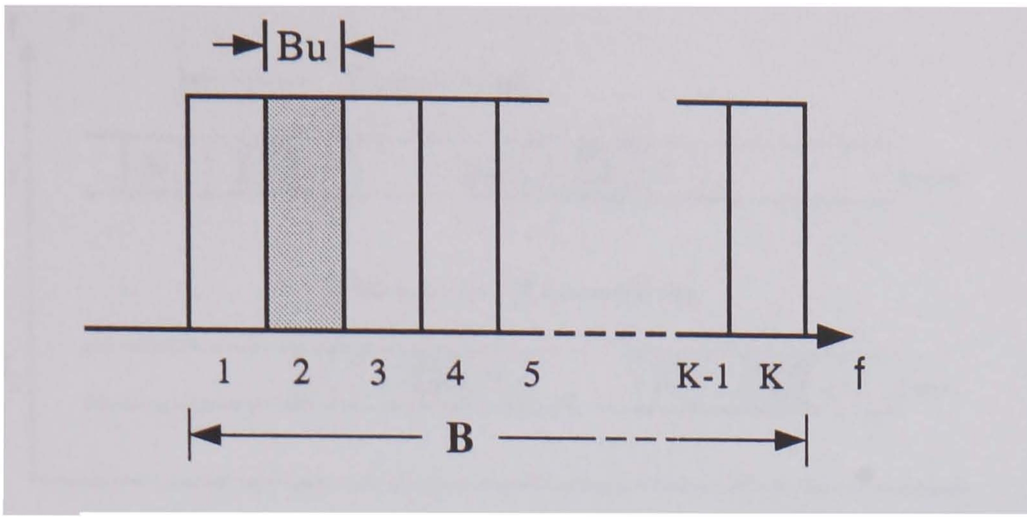

Figure 2.7: FDMA channel System

also be used with time division duplex (TDD), where only one band is allocated for all channels, but the transmission time on the link is split into time frames. Half of a time frame is for transmission, the other for reception. The result of which has a limiting effect on the number of independent data streams, or channels, which could be used within a specified bandwidth of the spectrum.

In order that as many channels as possible can be utilised by FDMA, high power, narrowband communications systems were developed, such as narrowband FM. These attempt to use as much of the transmitted frequency waveform to convey information as possible, using high power to combat noise and to extend the range of coverage provided. Unfortunately, this approach has led to overcrowding of the lower end of the spectrum.

The efficiency of FDMA relies on each user requiring the use of the network for a large percentage of the time. If this is not the case, then the available bandwidth is being wasted, since other users could have been using it instead.

2.6.2 TDMA

Time Division Multiple Access (TDMA) is a digital cellular communications access technique which offers a potential threefold increase in capacity over conventional FDMA systems [3]. TDMA operates not only by being able to divide up the available spectrum in frequency, but also to divide up the use of each available channel in time as well. Consider a system in which the user traffic is organised into frames of length Tsecs, each frame contains K slots with a transmit and receive frequency of f_1 and f_2 respectively. Each user is assigned to a slot for the duration of a call. This situation is shown in Figure 2.8.

However, for satisfactory operation, all users must be synchronised to access the radio channel at fixed moments, or else they would interfere with each other. For example, consider mobiles in a multipath environment (Section 4.2), where the transmission time to each mobile from a base station is quite different and multiple arrival times of the same signal

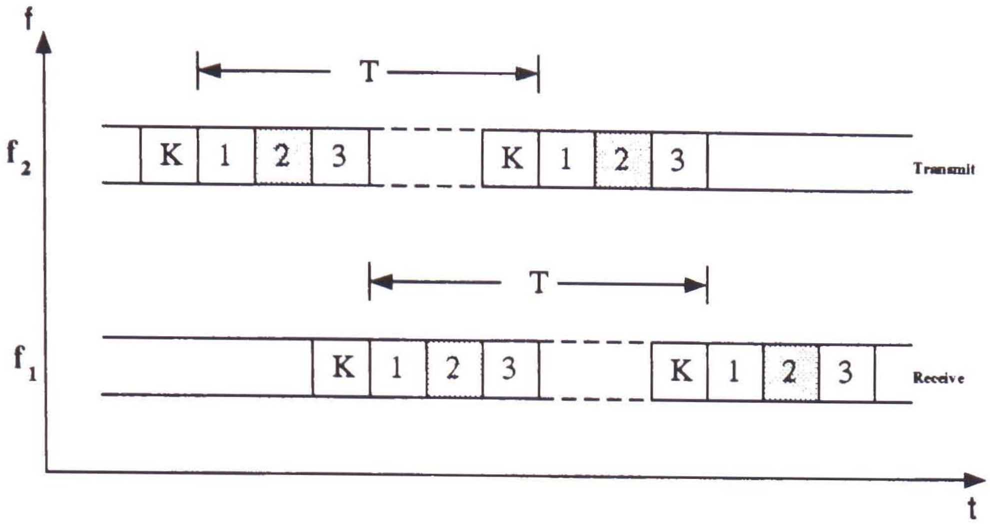

Figure 2.8: TDMA Channel/Frame System

are possible. In this case, sophisticated timing and synchronisation techniques are required to compensate for unequal arrival times between frames and estimate interference [20].

TDMA has since been developed in such systems as DECT (Digital European Cordless Telecommunications) and it holds a strong position as a contender from the fact that much of the technology required for a future development in the system is already in existence [21]. It also follows that operators currently using such systems are likely to be reluctant to change to an unknown and largely unproven system, not to mention the considerable investment that they have already made into the hardware to support current TDMA systems. In this case, it would be more sensible if the future cellular system could use part or all of the hardware already installed.

2.6.3 Spread Spectrum - CDMA

"Spread spectrum is a communication technique in which a transmitted signal occupies a bandwidth in excess of the minimum necessary to send the message information. The spreading of the bandwidth is accomplished by means of a data-independent code requiring synchronised reception with the code at the receiver to de-spread and recover the data" [22].

Although not considered for use in a cellular communications systems until recently, CDMA is not a new technology. It has been used in military applications for decades, mainly because of the low-detection and secrecy aspects which it exhibits and as a result much of the literature was classified. It was only more recently that interest in the area, such as shown by the U.S. company Qualcomm Inc. [23] in the late 1980's, that CDMA has been brought to the forefront of people's attention as a viable air interface technique.

Unlike previous analogue and digital systems, CDMA systems enable multiple conversations to take place within the same bandwidth by means of a 'noise-like' sequence, which is used to spread the data across the available bandwidth. Only with prior knowledge of this sequence at the receiver is it possible to separate/differentiate the individual users. Figure 2.9 demonstrates this principle. Furthermore, with the capability of having multiple users in the same frequency band throughout the network (see Section 3.2.3), a system employing this approach would require little frequency planning, or channel allocation, which is commonly a major aspect of the network planning process.

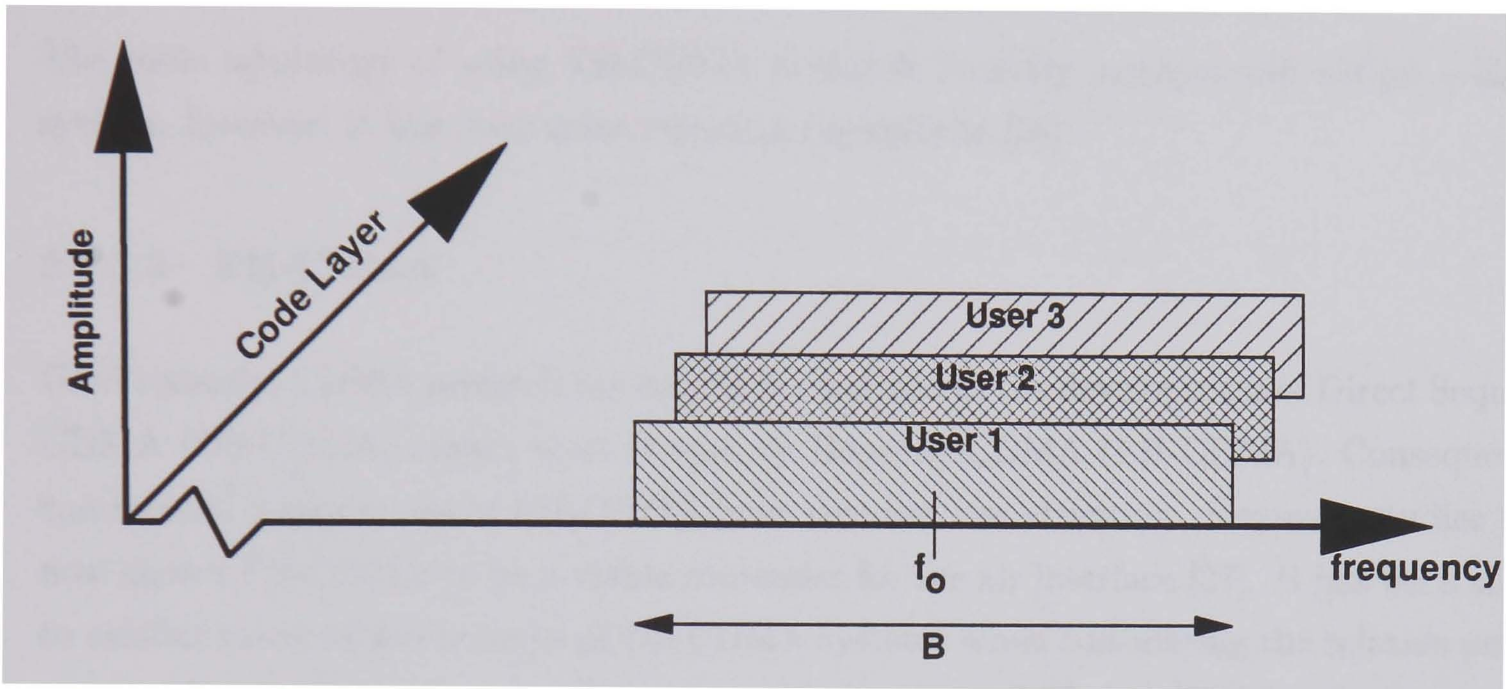

Figure 2.9: Code layering in a CDMA System

The basic operation of a CDMA system has been compared with conversations at a cocktail party [24] where everyone present is allowed to speak at the same time, but to use different languages for each conversation. All a listener has to do, is to listen for their particular language to hear what is being said to them, the other languages present mearly acting as noise.

Currently in the US, licences have been granted to a variety of CDMA systems in the PCS frequency bands [25].

2.6.3.1 TH-CDMA

In a Time Hopping CDMA (TH-CDMA) system, the carrier is transmitted in rapid bursts at time intervals determined by a pseudo-random spreading sequence. The time-domain format of a TH-CDMA signal is shown in Figure 2.10. Data is transmitted in bursts of k bits in a pseudo-random time-slot duration of T_f/M seconds, where T_f is the duration of the a TH frame and M is the number of available time slots in each frame.

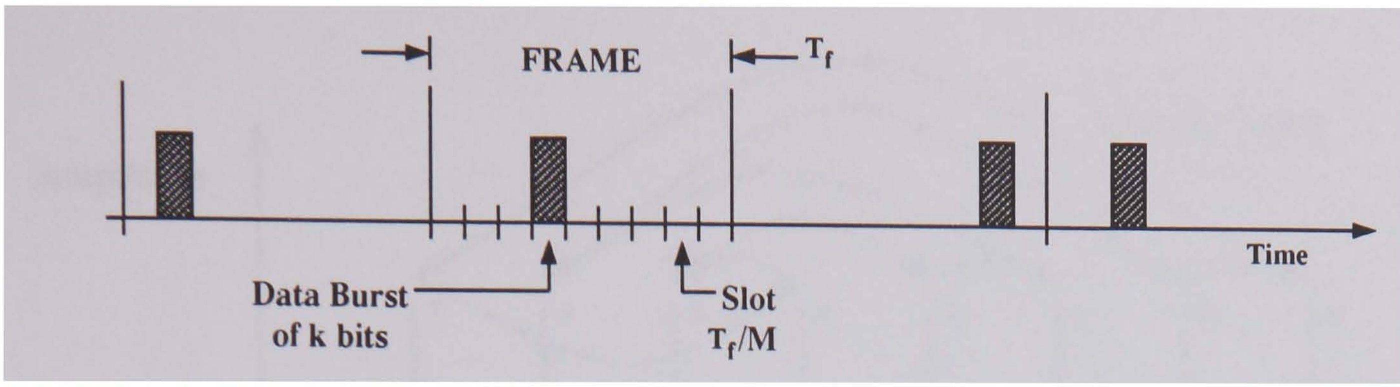

Figure 2.10: TH-CDMA Signal Format

The main advantage of using TH-CDMA is that it is easily incorporated within a digital system, however, it has poor noise rejection capabilities [26].

2.6.3.2 FH-CDMA

Until recently, CDMA research has largely been aimed at the development of Direct Sequence-CDMA (DS-CDMA) rather than Frequency Hopping-CDMA (FH-CDMA). Consequently, commercial applications of FH-CDMA have received less attention. However, studies have now shown FH-CDMA to be a viable contender for the air interface [27]. It has been shown to exhibit many of the benefits of DS-CDMA systems when considering the relative performance of low and medium rate data bearers for both the PCS and UMTS environments. It has also been shown that FH-CDMA does not require power control to the same stringent level as would be required of a comparable DS-CDMA system [28].

A frequency hopping system operates by rapidly and discretely shifting its carrier throughout the available bandwidth, using a pseudo-random frequency-shift or *"hopping"* pattern. Hopping frequencies are typically of the order of a few hundred hops per second: e.g the US company Geotek uses a system with a hopping frequency of 150hps for a data rate of 15kbs [29], while Motorola uses a 500hps system with a data-rate of 500kbps [30].

Figure 2.11 shows an example of the spectrum of a simple FH-CDMA system. This hopping sequence effectively scatters the user's data over the available bandwidth. By using the same pattern in the receiver down-conversion process, it is possible to re-tune the receiver to the correct new frequency at the end of each hop, to re-obtain the user's data. Data modulation of the carrier is traditionally by Frequency Shift Keying (FSK) [31], although there is now considerable interest in linear modulation, in particular Quadrature Phase-Shift Keying (QPSK) [32].

2.6.3.3 DS-CDMA

Interest in Direct Sequence CDMA (DS-CDMA) as an air interface technique has essentially been inspired through the development of the technology and extensive marketing

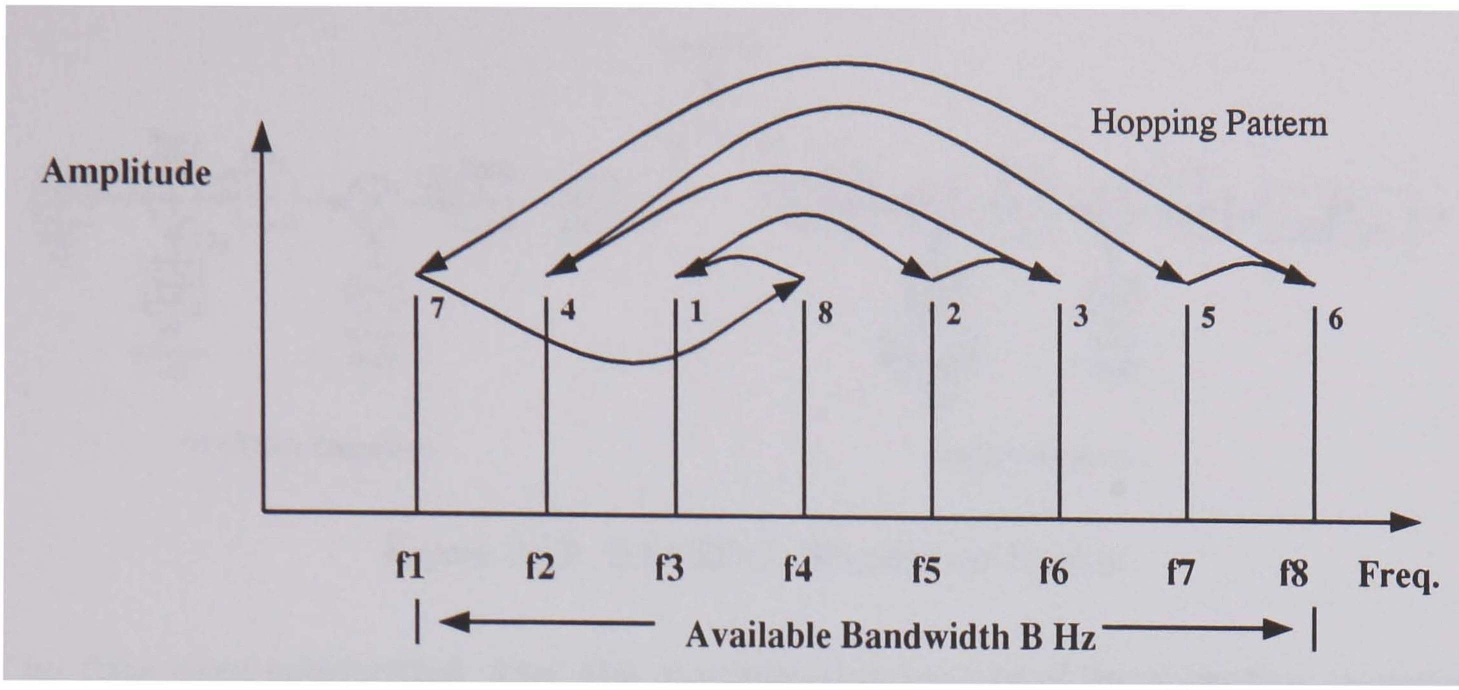

Figure 2.11: Transmitted Spectrum of a FH-CDMA System

campaign of the US company Qualcomm Inc. Studies have shown DS-CDMA[2] to offer a long term capacity for wireless communications [33] [34] which have recently been substantiated through the simulation work [35] and field trials performed [36] [37]. In particular Qualcomm have made claims which put the capacity of DS-CDMA a factor of 4 to 6 ahead of TDMA or FDMA and nearly a factor of 20 ahead of FM/FDMA [23]. Interest outside the US, encouraged by this work, has also been shown e.g. the Code Division Testbed (CODIT) project within RACE [38] and the U.K. the SERC/DTI LINK Personal Communications programme (Section 1.2.5), both of which have the main objective of evaluating CDMA for a third generation mobile communications system like FPLMTS or UMTS.

DS-CDMA uses a double modulation process on the data to be transmitted, first using a pseudo-random *"noise"* sequence (Section 4.5) to produce an encoded wideband signal, which is then used to modulate an RF carrier (usually BPSK, QPSK or even MSK). The order of modulation could just as easily be reversed i.e. firstly RF carrier modulation followed by the pseudo-random spreading sequence.

The pseudo-random spreading sequences used operate at data-rates or *"chipping"* frequencies much higher than those used in FH-CDMA systems. In the Qualcomm demonstration system, a relatively narrowband 1.25MBits/s spreading sequence is used [10], although figures of at least 5MBits/s [39] have been suggested to mitigate multipath effects.

A simple DS-CDMA transmitter and receiver system is shown in Figure 2.12 and the signal spectra taken at various points in the transceiver system are shown in Figure 2.13.

Point (1) in Figure 2.13 shows the spectrum of a data sequence $d(t)$ at a data rate f_dHz, which is used to modulate a spreading sequence $c(t)$ with a chipping rate $f_c$chips/s (with a spectrum shown in (2)).

[2]Referred to as only *CDMA* by Qualcomm Inc.

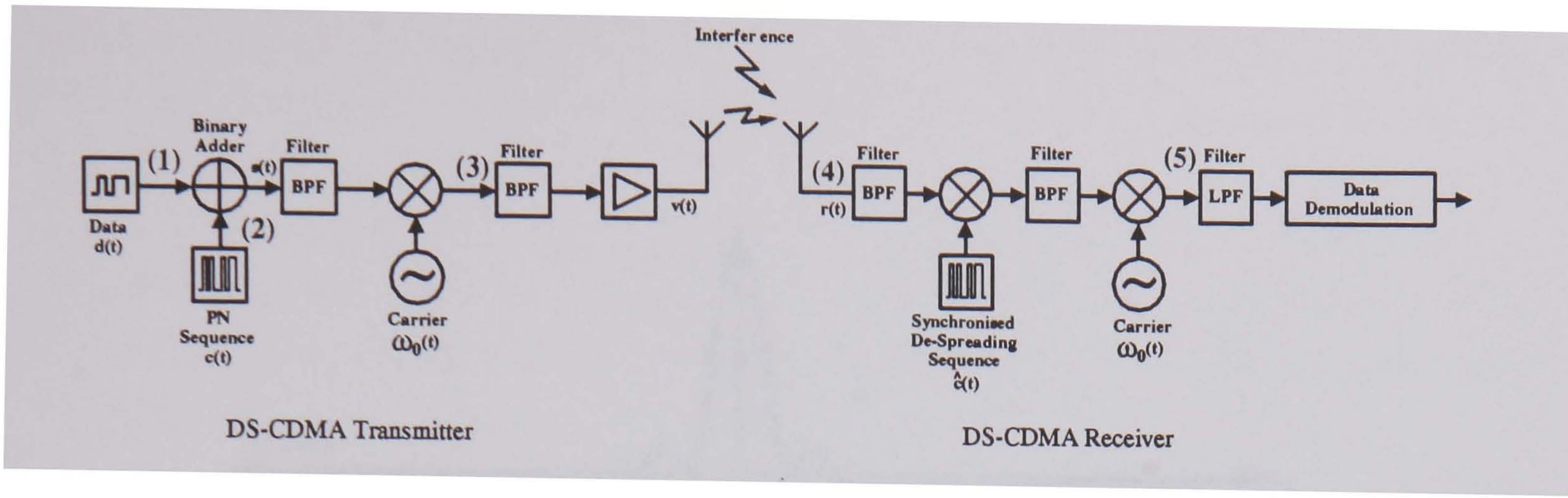

Figure 2.12: DS-CDMA Transceiver System

If no data were transmitted, then the multiplication process of the spreading sequence of length L chips and the carrier would produce a wideband suppressed-carrier signal centred at f_oHz, with a power spectral density distribution consisting of discrete lines spaced at frequency intervals of $1/Lt_c$Hz. The envelope of the distribution having the form:

$$S(f) = \frac{t_c}{2}\left[\frac{Sin(\pi t_c)}{\pi f t_c}\right]^2 \tag{2.2}$$

where t_c is the spreading code chip duration.

The central part of this power distribution or *"main lobe"* from (f_o - f_c)Hz to (f_o + f_c)Hz contains 90% of the transmitted power. The sidelobes, having zeros spaced every f_cHz from the centre f_oHz, are usually attenuated by filtering in the transmitter, to reduce out-of-band interference.

The spreading process (multiplication of the carrier by the spreading sequence) distributes the power contained within the carrier signal over a bandwidth equal to twice the chip rate of the code (Section 3.2.2.2). As a result, the transmitted signal has a lower power spectral density.

In the system shown in Figure 2.12 the output signal produced by the modulation of the carrier by the data and PN sequence would have the form:

$$v(t) = \sqrt{2P_s}c(t)d(t)cos\omega_c t \tag{2.3}$$

where P_s is the average signal power and ω_c is the carrier frequency in radians.

An ideally filtered version of the transmitted signal (i.e. sidelobes removed to prevent out-of-band interference) is shown in Figure 2.13 (3). It is also assumed here that the chipping rate f_c is much higher than the data rate f_d.

At the receiver, the spreading process is reversed by multiplying the received signal with a synchronised version of the original spreading code $\hat{c}(t)$. After appropriate filtering this process *collapses* the received signal power back to the original data bandwidth. Unwanted

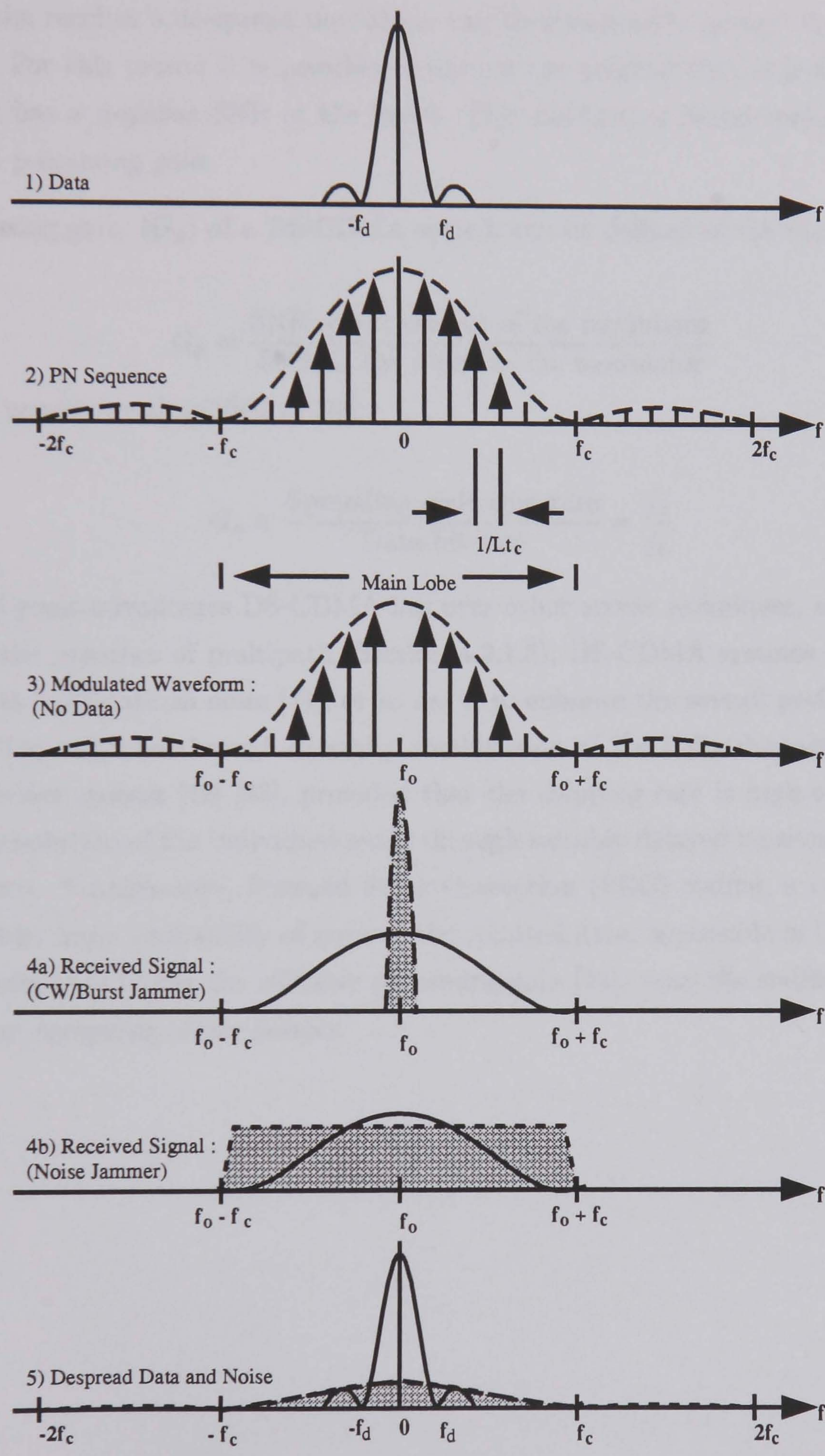

Figure 2.13: Spectra of Signals in a DS-CDMA System

signals present at the receiver input, such as those shown in Figure 2.13 (4a) and (4b), having no correlation with the spreading sequence used, are effectively *spread* by the multiplication with the receiver's code. As a result, the signal-to-noise ratio (SNR) at the output of the receiver's de-spread modulator can be significantly greater than the SNR at the input. For this reason it is possible to extract the original data sent from a received signal that has a *negative* SNR at the input. This function of signal spreading is termed the system *processing gain.*

The processing gain, (G_p) of a DS-CDMA system can be defined as the ratio:

$$G_p = \frac{\text{SNR at the output of the modulator}}{\text{SNR at the input to the modulator}} \tag{2.4}$$

which can usually be simplified to [40]:

$$G_p \equiv \frac{\text{Spreading code chip rate}}{\text{Data bit rate}} = \frac{f_c}{f_b}. \tag{2.5}$$

One of the great advantages DS-CDMA has over other access techniques, such as TDMA, is that in the presence of multipath (Section 4.2.1.3), DS-CDMA systems can be used to either reject multipath as noise [41], or to use it to enhance the overall performance of the system. This could be through diversity combination of the individual signal paths in a RAKE receiver system [42] [43], provided that the chipping rate is high enough to allow temporal resolution of the individual paths through suitably delayed versions of the spreading sequence. Furthermore, Forward Error Correction (FEC) coding, a coding sequence which enables lower probability of error in the received data, is possible in Direct Sequence systems *without* reducing the effective processing gain [44], since the coding forms part of the inherent spreading of the system.

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Chapter 3

DS-CDMA Quality of Service

QUALITY-OF-SERVICE: ***"The collective effort of service performances which determine the degree of satisfaction of a user of the service"*** - CCITT, *"Handbook on Quality of Service and Network Performance."* [1]

3.1 Introduction

In this chapter the concept of Quality-of-Service (QoS) is introduced with respect to a communications system. The relevant measures of system performance are discussed from the network and user's point of view. Further to this, the capacity of a simple cellular system is estimated using a simulation study with a pre-defined minimum signal quality level. Also, the effects of the handover technique adopted and its sensitivity to changes in system parameters is explored.

3.2 Quality-of-Service and Network Performance

The next generation of cellular systems is expected to provide as good a quality wireless communications service as can currently be supplied by the fixed Public Switched Telephone Networks (PSTN), but on a global roaming basis. In order that this can be achieved, the Quality-of-Service (QoS) measures have to be established and satisfied at the early stages of the development of such a system.

The QoS of a particular cellular system can have many measures, some based on the requirements of the network operator and others on the perceptions of the end-users, although it is widely accepted which the QoS can be "user driven" [1] [2]. The end-user's perception of what makes a good quality system (and what sells a system) is perceived from the operability of the end product rather than the system architecture that has made it. This places a requirement on the handover technique adopted within the network. The technique must be able to maintain call integrity and link reliability, whilst, ideally, remaining a *"transparent"* process to the user, irrespective of service required, user location, terminal type, air interface(s), etc.

The main demands of the end-users can be categorised as follows :

- Terminal simplicity.
- Reliability in both connection and signal quality.
- Flexibility in both features and services offered.
- Affordability in both acquisition of equipment and usage.

3.2.1 QoS Parameters

QoS parameter measurements are subject to statistical as well as objective analysis: for example, voice transmissions across a link can be recorded and played back later. The link quality judged by a Mean Opinion Score (MOS) [1]. Quality measures commonly used to establish link signal quality for services such as voice, data and Integrated Voice and Data (IVD) are shown in Table 3.1 [3]. QoS measures have to be determined for each service offered and for a variety of conditions: e.g. different cellular environments, power control algorithms, bit rates, handover techniques, etc., to establish the system sensitivity to these parameters as well as to determine the likely system capacity.

Signal-to-Interference-Noise-Ratio (SINR) is one such measure commonly used to estimate the channel quality, either from the minimum value which will guarantee reliable communications over the channel or from the short-term variability of this value [4].

In a cellular system, handover must be able to provide a minimum level of quality which will not be degraded during its operation. But more importantly, handover should actually improve the system quality.

QoS Measure	Voice	Data	IVD
BER or SNR	No	Yes	Yes
MOS	Yes	No	Yes
Delay	Yes	Yes	Yes

Table 3.1: Multi-media QoS Parameters

3.2.2 Noise Performance

The noise performance of a system is a fairly critical aspect in the design of a radio communications link. Normally determining radio coverage from a central transmitter is complicated by the interference in the network from frequency re-use in adjacent cells, particularly in the case of microcellular systems [5]. However, this is not the case for CDMA, which can operate with a frequency re-use factor of one (Section 3.2.3), hence all users operate within the same frequency bandwidth throughout the network, using code orthogonality to separate them at the receiver.

In addition to this multi-user interference, the presence of noise in a DS-CDMA system can be from many other sources, either intentional or unintentional. These interfering signals include, random noise, pulsed noise, partial band interference and single tone (CW) or multitone interference. A DS-CDMA system's robustness to the presence of these noise sources determines its performance and capacity capabilities (Section 3.2.4).

3.2.2.1 Thermal Noise

Assuming a BPSK communications system incorporating a spread spectrum technique, thermal noise introduced into the system through the channel is modulated in the receiver by a despreading sequence $g(t)$. However, by its very nature, there will be no effect on the power spectral density nor the probability density function of Gaussian noise. Hence the statistics of the noise behaviour are unaffected by the spreading technique and the overall effect on the system is the same as for a similar system not incorporating a spreading technique i.e. in a BPSK spread spectrum system, the error probability will remain the same for a non-spread spectrum system [6] :

$$P_e = 0.5\text{erfc}\sqrt{E_b/N_0} \tag{3.1}$$

where E_b is the energy per bit and $N_0/2$ is the two-sided power spectral density of the noise.

3.2.2.2 Multiple Access Interference

In a CDMA scheme, each user is given an individual and distinctive PN code (Section 4.5). For this analysis, each user is assumed to use the same length code, which has no correlation with any other code, i.e. codes are assumed to be very long and ideal.

If k users are transmitting simultaneously, using the same carrier frequency, f_o, each using one of a group of ideal PN codes, $g_i(t)$, the received signal at the receiver for user i will have the form:

$$v(t) = \sum_{i=1}^{k} \sqrt{2P_s} g_i(t) d_i(t) cos\,(\omega_0 t + \theta_i) \tag{3.2}$$

where each signal is assumed to be received at the signal strength, P_s. The PN sequences $g_i(t)$, all have the same chip rate, f_c chips/sec, and $d_i(t)$ is the user's transmitted data which has a data rate of f_b bits/sec. Due to propagation characteristics of the channel (Section 4.2), the signal is received with a random phase component, θ_i rads. It is also assumed, for simplicity, that signal strengths at the receiver are sufficiently large that thermal noise can be ignored.

At each of the k possible correlators in the receiver, the incoming signal is multiplied by the relevant phase aligned signal to decorrelate the appropriate users data e.g. for user 1, the output of this ideal correlation process would be:

$$v_{01}\prime = \sum_{i=1}^{k} \sqrt{P_s} g_1(t) g_i(t) d_i(t) cos\,(\theta_i - \theta_1) \qquad (3.3)$$

Assuming correlation between only the user's transmitted code and that at the receiver, Equation 3.3 becomes:

$$v_{01}\prime = \sqrt{P_s} d_1(t) + \sum_{i=2}^{k} \sqrt{P_s} g_1(t) g_i(t) d_i(t) cos\,(\theta_i - \theta_1) \qquad (3.4)$$

Thus, user 1's transmitted data is recovered and the other users' signals are spread by the receiver code $g_1(t)$. The signals from the other users can effectively be regarded as k-1 independent interfering noise sources.

It can be shown [7] that under these conditions, a low probability of error can be maintained if the processing gain G_p of the system is adjusted such that:

$$\frac{f_c}{f_b} \gg (k-1)/2 \qquad (3.5)$$

Hence if this ratio is not altered, then the system performance will be limited by the number of users present in a system, assuming that all the users are sufficiently power controlled to be received at the base station with an approximately equal signal strength.

However, if an unwanted, or 'rogue' user's signal is received at a much higher level than another desired user's signal, either due to their proximity to the receiver or transmission power, then errors are likely to occur. This problem is known as the *near-far* effect and can severely degrade system performance.

3.2.3 Universal Frequency Re-Use

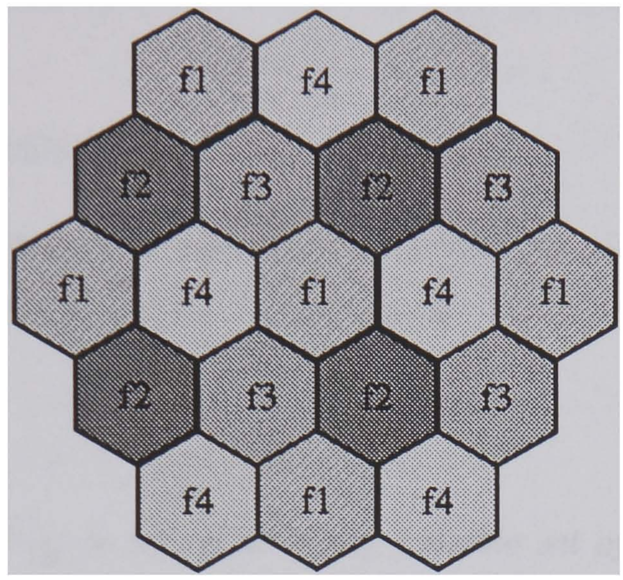
Frequency re-use is a technique whereby the same frequency bandwidth used in a cell can be used in a second, distant cell within the same cellular network.

The minimum distance between cells before co-channel interference reaches an unacceptable level, depends on the rate at which signals are attenuated in the environment and the maximum sustainable interference level to allow reliable system operation.

Having established the minimum re-use distance, it is then possible to calculate the minimum number of frequency bandwidths required by the system to provide full coverage for the entire network, using a re-use pattern. This gives rise to the *frequency re-use factor* K. This can then be used to calculate the minimum bandwidth required by the cellular system:

$$B_{min} = KB_{cell} \tag{3.6}$$

where B_{cell} is the minimum bandwidth required per cell. Figure 3.1 shows the frequency re-use pattern for a factor of $K = 4$, each colour corresponding to a different frequency bandwidth allocation per cell.



Frequency Allocation for a
Re-Use Factor K = 4

Figure 3.1: Frequency Re-use Pattern in a Cellular System

However, unlike other systems which require separate channels to be allocated within a cell to distinguish users or groups of users e.g. FDMA or TDMA (Section 2.6), a DS-CDMA system can operate with a frequency re-use pattern of $K = 1$ i.e. the same frequency can be used throughout the network, using code orthogonality to separate users at the receiver and greatly easing the frequency planning and management of the system. In fact, a DS-CDMA network would only require to allocate one frequency band for the mobile-to-base station link (or uplink) and one for the base station-to-mobile (or downlink) [8]. No further frequency or time division of the bands would be required.

3.2.4 Capacity

Capacity can be defined as the simultaneous number of variable rate voice sources that can be supported per cell while achieving a target bit-error-rate (BER).

3.2.4.1 Channel Capacity Theorem

The idea of channel information capacity was developed by C. E. Shannon [9] over 45 years ago.

Theorem 1: *Given a source of M equally likely messages, with $M \gg 1$, which is generating information at a rate R. Given a channel capacity C. Then, if*

$$R \leq C \tag{3.7}$$

there exists a coding technique such that the output of the source may be transmitted over the channel with a probability of error in the received message which may be arbitrarily small.

The negative statement of this is:

Theorem 2: *Given a source of M equally likely messages, $M \gg 1$, which is generating information at a rate R; then if*

$$R > C \tag{3.8}$$

the probability of error is close to unity for every possible set of M transmitter signals.

The most important theorem, which is complementary to Shannon's theorem and directly applicable to spread spectrum systems, is the Shannon-Hartley Theorem which applies to a channel in which noise is assumed to be Gaussian in nature, which states

Theorem 3: *The channel capacity of a white, bandlimited Gaussian channel is*

$$C = B\log_2\left(1 + \frac{S}{N}\right) \text{ bits/s} \tag{3.9}$$

where B is the channel bandwidth, S is the signal power and N is the total noise power within the channel bandwidth.

For restricted bandwidth communications systems such as FDMA and TDMA (Section 2.6), a high transmit power is used to achieve a desired channel capacity. However, in the case of spread spectrum techniques, where the channel bandwidth can be controlled through a spreading sequence, using more bandwidth lowers the required signal-to-noise ratio for the same capacity. Hence wide bandwidth systems are capable of operating at a much reduced power compared with their narrowband counterparts.

For spread spectrum applications it is usual to quote Equation 3.9 in terms of the energy per bit to noise power ratio, E_b/N_0, as:

$$\frac{C}{B} \leq \log_2\left[1 + \frac{R}{B}\frac{E_b}{N_0}\right] \text{ bits/s/Hz} \tag{3.10}$$

3.2.4.2 Bandwidth Efficiency

Bandwidth efficiency is a measure of how well a system can use the available frequency band to transmit user's data and hence gives a capacity limit for the system. If a DS-CDMA system is considered, which transmits an R_b bits/s data stream with a spreading code at R_c chips/s, where $R_c \gg R_b$, then the required bandwidth for transmission would be R_c/R_b times that required for sending the unspread data. Further to this, assuming that the system has M orthogonal codes, each corresponding to one of N simultaneous users in a bandwidth B_THz, the bandwidth efficiency, η, may be given by:

$$\eta = \frac{\text{Number of Users} \times \text{Data rate per user}}{\text{Total transmission bandwidth}} = \frac{NR_b}{B_T}\text{bits/Hz} \tag{3.11}$$

For synchronous CDMA [10], where all users codes are running at exactly the same frequency, the maximum number of users may be given by:

$$N_{max} = K\left[\left[\frac{E_b}{N_0}\right]^{-1} + 1\right] \tag{3.12}$$

and the bandwidth efficiency becomes:

$$\eta = 0.5\left[\left[\frac{E_b}{N_0}\right]^{-1} + 1\right] \tag{3.13}$$

For *asynchronous* CDMA the maximum number of users is:

$$N = \left[3K\left[\frac{E_b}{N_0}\right]^{-1} + 1\right] \tag{3.14}$$

and bandwidth efficiency is:

$$\eta = \frac{3}{2}\left[\frac{E_b}{N_0}\right]^{-1} \tag{3.15}$$

3.2.4.3 DS-CDMA Capacity

In a DS-CDMA system, multiple-users can share a common transmit frequency, using spreading code orthogonality to separate them at the receiver (Section 2.6.3.3). In this situation, unwanted signals or users form a background noise to the wanted signal. The level of this background noise is directly related to the power of the other user's signals. If it is assumed that all other users have identical transmit powers and identical propagation losses, then a worst-case estimate of the number of users in a system can be calculated with a few assumptions. If all other users can be considered as additive white Gaussian noise

(AWGN), then neglecting other noise sources (e.g. spurious and thermal) as negligible in comparison to each user's signal power S received, the SNR at a receiver is given by

$$SNR = \frac{S}{S(N_{Users} - 1)} = \frac{1}{N_{Users} - 1} \tag{3.16}$$

where S is the received signal power from each user and N_{Users} is the total number of users. E.g if the required input SNR is -20dB then 100 simultaneous users can be supported by such a system.

For a better estimate and for reliable system operation, then consideration is given to the energy-to-noise density ratio. This results in the following equation:

$$\frac{E_b}{N_0} = \frac{S/R}{(N_{Users} - 1)\, S/B_T} = \frac{B_T/R}{N_{Users} - 1} \tag{3.17}$$

where E_b is the energy per bit, N_0 is the noise power spectral density, R is the information bit rate and B_T is the total bandwidth of the transmitted signal.

If thermal noise were included, Equation 3.17 then becomes:

$$\frac{E_b}{N_0} = \frac{B_T/R}{(N_{Users} - 1)} + \frac{N_0}{S} \tag{3.18}$$

This then implies that the capacity of the system in terms of the number of the users is

$$N_{Users} = 1 + \frac{B_T/R}{E_b/N_0} - \frac{N_0}{S} \tag{3.19}$$

where B_T/R is generally referred to as the *"processing gain"* and the value for E_b/N_0 is the value required for adequate performance of the modem and decoder, which for voice transmission implies a BER of 10^{-3} or better. For terrestrial systems, this is limited by the transmitter's power level. The required E_b/N_0 has been quoted as 7dB for a reverse link or *uplink* and only 5dB for the forward link or *downlink* [11] using dual antenna diversity and a relatively powerful convolutional code (constraint length 9, rate 1/3).

Further improvements on the capacity of a DS-CDMA system are possible by employing frequency re-use, voice activity detection and cell sectorisation. The full equation used by Qualcomm [12] to calculate capacity is given as :

$$N = \frac{B_T}{R} \times \frac{1}{E_b/N_0} \times \frac{1}{D} \times K \times G \tag{3.20}$$

where D is the voice duty cycle, K is the frequency re-use factor and G is the number of sectors per cell. As an example, for a system using B_T = 1.25MHz, R = 9600bps,

E_b/N_0 = 6.0dB, D = 50%, K = 60% and G = 3 sectors, gives a radio link capacity of around 120 channels per cell.

3.3 DS-CDMA Handover Simulation Study

The enhanced simulation model which has been developed was based on the work of earlier capacity studies [13] [14] [15], which dealt primarily with CDMA cellular systems incorporating hard handover. The model employs a *"Monte-Carlo*[1]*"* approach to calculating the downlink capacity for both hard and soft handover techniques in an *asynchronous*, interference-limited DS-CDMA multi-cell system.

The simulation environment consists of a series of hexagonal cells arranged in tiers around a central cell. Mobile stations are then deployed at random over the entire cellular system. Using the co-ordinates of the base stations in each cell and appropriate propagation fading statistics, it is then possible to link mobile stations with base stations according to an assignment algorithm based on either hard or soft handover techniques. The statistics of each mobile station connected to the central base station (BS0) can then be calculated.

From these mobile station statistics an estimate of the system's performance and hence capacity can then be calculated according to a maximum outage requirement. Using this approach, the sensitivity of each handover technique to various system parameters can also be assessed.

3.3.1 Downlink Simulation Model

The simulation model locates a base station at the centre of each hexagonal cell. The cells are located on a tier system where, in the case of a single cell study, the number of tiers would be $N_{Tiers} = 1$.

Mobiles are randomly placed within the simulation environment on an (x,y) co-ordinate basis, relative to the central base station, (BS0), positioned at the co-ordinates (0,0). The mobile's co-ordinates, x and y, are each zero mean, random Gaussian variables such that :

$$|\,(x,y)\,| \leq R_{user} \tag{3.21}$$

where R_{user} defines a circle, centre (0,0), with an area equal to the area covered by a cellular tier structure containing N_{BS} base stations.

[1] A repetitive, random deployment of groups of mobile stations.

$$R_{user} = R_{hex} \times \sqrt{\left(N_{BS} \times \frac{3\sqrt{3}}{2\pi} \right)} \tag{3.22}$$

Figure 3.2 shows the approximate layout of the system for a two tier case ($N_{Tiers} = 2$), with a random deployment of 6 mobile stations.

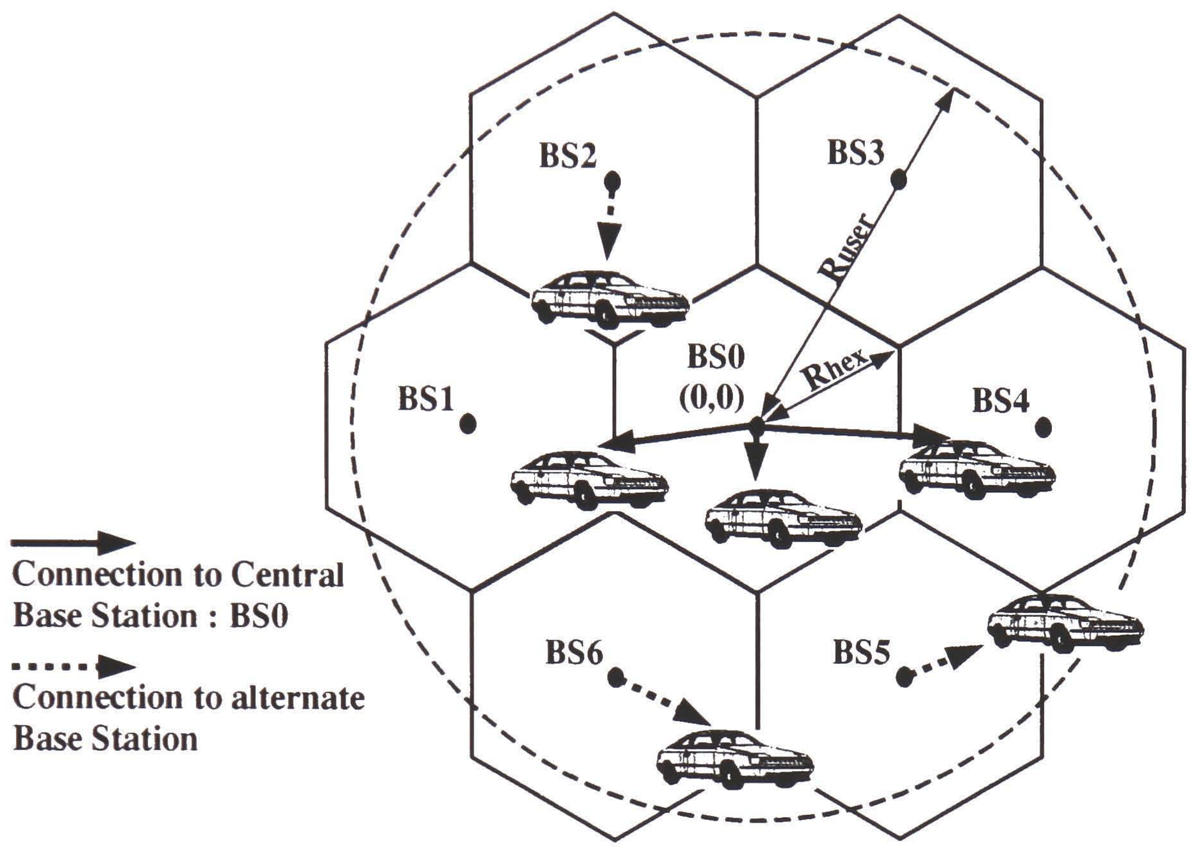


Figure 3.2: Random Deployment of 6 Mobiles in a 2 Tier Environment

In the case of a single cell analysis, all signals arriving at a mobile will be from the central base station and subject to the same fading and attenuation as the subscriber's signals on the uplink. However, in a multiple cell study, ($N_{Tiers} > 1$), then interference can be derived from base stations in the surrounding tiers of cells.

In the simulation studies performed, the following assumptions have been made about operational parameters of the base stations:

- All base stations are assumed to use omni-directional antennas.
- A separate band is allocated for the uplink and downlink, as in Frequency Division Duplex, so that it can be assumed that they do not interfere.
- All base stations transmit at full power.
- Of the available power at the base station, a fraction β of that power is available to be transmitted to the connected users. The fraction $1 - \beta$ is allocated exclusively to the pilot signal, which would be used for power measurements by the mobiles and hence acts as interference to the call channels.

- The base station is assumed to divide up the available power to the users equally i.e. for N_{Users} users connected to a base station, the signal transmitted from the base station to the ith connected mobile user, Φ_i, will be :

$$\Phi_i = \Phi = \frac{1-\beta}{N_{Users}} \qquad i = 1...M \tag{3.23}$$

- The user load per cell is the same as for the central cell on each iteration.

Signal strength calculations from a base station to a particular mobile station are made using propagation path loss and shadowing components (Section 4.2). Other noise sources e.g. thermal noise, are assumed to be negligible in comparison to received signals from active base stations. If S_{i_j} is the total power received by mobile station i from a base station j, then:

$$S_{i_j} = r_{i_j}^{-\alpha} 10^{\xi_{ij}/10} \tag{3.24}$$

where α is the path loss exponent and ξ is a zero mean Gaussian random variable with standard deviation σ_{log}.

Then it follows that the total power received by that mobile from all N_{BS} base stations will be:

$$S_{i_{total}} = \sum_{j=1}^{N_{BS}} S_{i_j} \tag{3.25}$$

Knowing S_{i_j} for a mobile in a simulation run, it is possible to allocate each mobile a communications link to at least one base station according to the channel assignment algorithm used, (Sections 3.3.2 and 3.3.3) until all channels in BS0 have been allocated. Knowing the received signal strengths for each mobile connected to the central base station, the carrier-to-interference ratio, C/I can be calculated from:

$$\gamma_i = \left(\frac{C}{I}\right)_i = \frac{S_{i_{wanted}}}{S_{i_{total}} - S_{i_{wanted}}} \tag{3.26}$$

This process is then repeated over a large number of iterations to establish an estimate of the system C/I-distribution, from which the system performance or outage probability can be predicted.

The outage probability, P_{out}, is defined as the probability of having a C/I-level less than the minimum required. This can be expressed as:

$$P_{out} = \text{Prob}\left[\frac{E_b}{N_0} \leq \left(\frac{E_b}{N_0}\right)_{Req}\right] = \text{Prob}\left[\gamma < \gamma'\right] \tag{3.27}$$

where

$$\gamma' = R\frac{(E_b/N_0)_{Req}}{B} \tag{3.28}$$

The capacity can then be found from the maximum number of users to achieve a required system reliability e.g. for a 99% reliable link, the capacity will be given by the number of users shown at the 1% outage probability level.

Figure 3.3 shows a flow chart for the full simulation process.

3.3.2 Hard Handover Channel Allocation

In an actual cellular environment, mobiles would be moving between cells and hence be handing over between base stations to maintain the best quality communications link available (Section 2.4).

However, in the simulation model, the route history of any mobile is unknown i.e. each mobile is randomly placed within the environment without relation to any previous deployment position or time. As a result, the process of handover cannot be directly simulated by this model. However, it is possible to estimate the effects of the handover process over the allocation of base station channels to mobile stations.

In the case of hard handover, a handover margin, Δ_{Thresh} is used to identify a group of mobiles which could be in the process of handover between two or more base stations. In the simulation, the received signal strength at a particular mobile from each base station is calculated and a list made of all base stations within Δ_{Thresh} dB of the strongest received signal. For example, for mobile i, a base station k can be a member of the list if:

$$r_{ik}^{-\alpha}10^{\xi_{ik}/10} > r_{im}^{-\alpha}10^{(\xi_{im}-\Delta_{Thresh})/10} \tag{3.29}$$

where m is the base station from which the maximum pilot signal strength is received at the ith mobile.

The mobile is then connected, at random and with equal probability, to one of the base stations on the list. In the case of only one base station being on the list i.e. the strongest received signal, connection can only be to that base station.

Once each of the available channels for BS0 has been allocated, the received signal $S_{i_{wanted}}$ can be calculated for each mobile user from:

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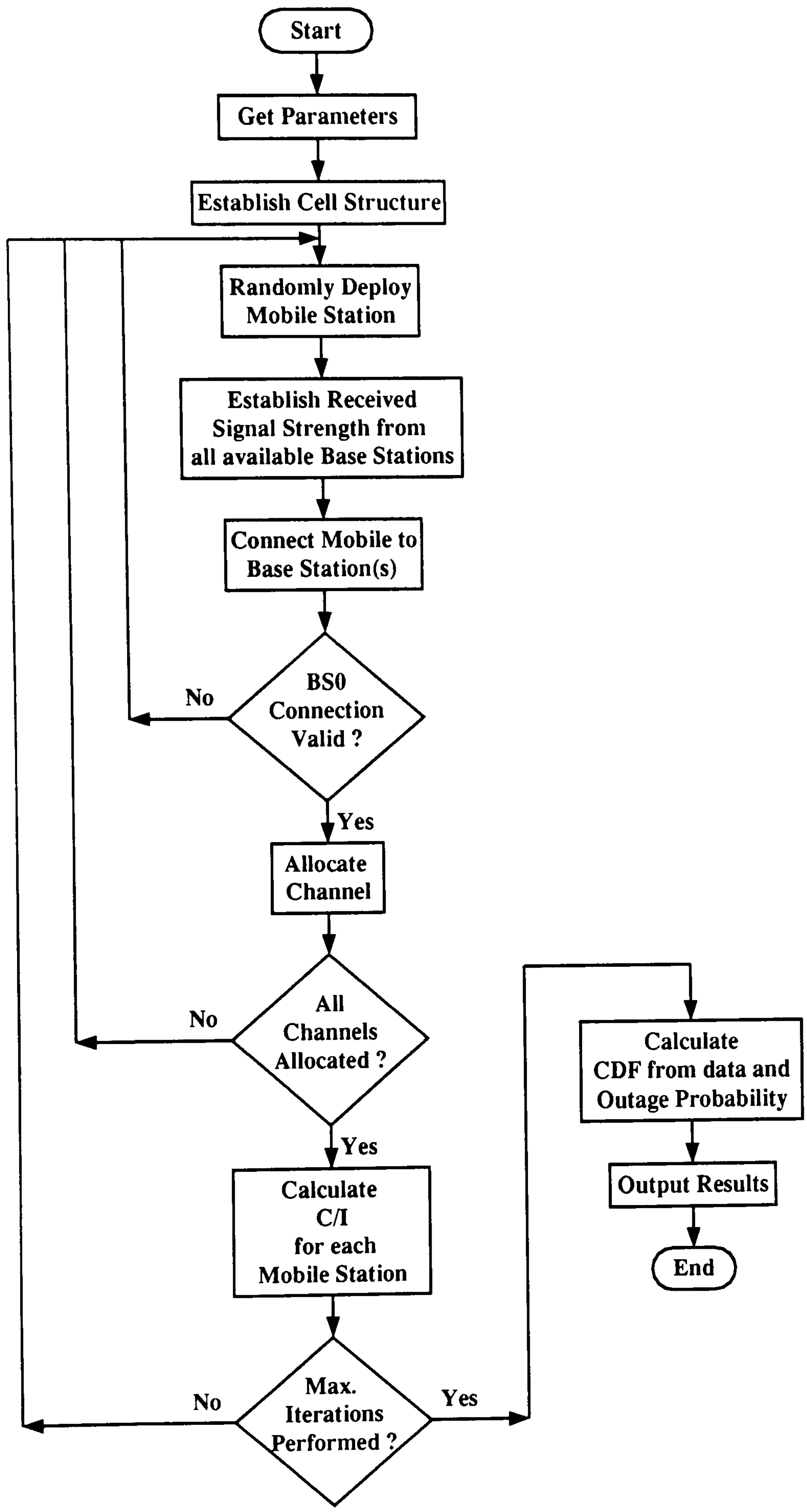

Figure 3.3: Flow Chart for DS-CDMA Capacity Simulation

$$S_{i_{wanted}} = \beta\Phi S_{i_j} = \beta\Phi S_{i_1} \tag{3.30}$$

where $j = 1$ corresponds to the central base station.

Equation 3.30 together with Equation 3.25 can then be used in Equation 3.26 to give the C/I for each mobile station.

3.3.3 Soft Handover Channel Allocation

In the case of soft handover (Section 3.3.2), each mobile station is capable of forming a link with more than one base station. In the simulation, each mobile could be connected to up to three base stations at a time, during the handover process.

The channel allocation is again performed on a threshold basis, whereby one or two base stations could allocate additional channels to a mobile station, if their received signal strengths lie within Δ_{Thresh} dB of the strongest base station, which is automatically connected to the mobile.

The received signal strengths at the mobile from all connected base stations can then be combined, in this case by Maximal Ratio Combining (MRC) (See Section 4.3).

For example, if a mobile i receives a maximum signal S_{m_0} according to Equation 3.24 where $j = m_0$, then it could connect to a further 2 base stations, m_1 and m_2 if:

$$S_{m_1} > S_{m_0} 10^{-\Delta_{Thresh}/10} \tag{3.31}$$

$$S_{m_2} > S_{m_0} 10^{-\Delta_{Thresh}/10} \tag{3.32}$$

$$S_{m_1} > S_{m_2} > S_j \qquad \forall j \neq m_0, m_1, m_2 \tag{3.33}$$

The total wanted received signal strength at the mobile from the base stations $S_{i_{wanted}}$ in Equation 3.26 now becomes :

$$S_{i_{wanted}} = \sum_{0 \leq k \leq 2} \beta\Phi S_{m_k} \tag{3.34}$$

3.3.4 Simulation Parameters

The system parameters used in the simulation study are shown in Table 3.2. Values were based on those used in previous capacity studies [13], which were used to simulate a system similar to that demonstrated by Qualcomm Inc [11]. Channel characteristics were taken over a range of typical reported values in propagation measurements and studies for microcellular environments [16] [17] [18].

Parameter	Symbol	Value/Range
Number Channels Available	N_{Users}	5→50
Number of Iterations	N_{Its}	2000
Voice Activity Factor	ν	50%
Pilot Power Fraction	β	20%
Distance Attenuation $r^{-\alpha}$	α	2, 3, 4
Standard Deviation of Log-normal Fading	σ_{log}	0dB, 8dB, 12dB
Handover Threshold Margin	Δ_{Thresh}	0dB→8dB
Required E_b/N_0 (dB) for BER $\leq 0.1\%$	$\left(\frac{E_b}{N_0}\right)_{req}$	5.0dB
User Bit Rate	R	8 kbits/s
Bandwidth	B	1.25 MHz
Number of Tiers (including BS0)	N_{Tiers}	4
Normalised Cell Radius	R_{norm}	1.0
Outage Probability	P_{out}	1.0%
Max. No. Links for Soft Handover	$Link_{max}$	3

Table 3.2: Downlink Simulation Parameters

3.3.5 Simulation Results

Results obtained from the simulation work show a promising system performance gain for the technique of soft handover to the more traditional technique of hard handover.

Figures 3.4 to 3.9 show the proportion of mobile stations (MS's) connected to base stations (BS) under the soft handover scheme as the handover threshold, Δ_{Thresh}, is increased under different propagation statistics. Due to the random placement of users throughout the cellular environment, the proportion of users in soft handover could be directly mapped to the relative size of the soft handover region. Obviously, hard handover, being a *break-before-make* process, has no similar associated region i.e. the mobiles can only connect to one base station and hence cannot be considered to be *"in handover"*.

As may be expected, it can be seen from these results that variation of the path loss exponent exhibits an inverse relationship between its value and the total proportion of users in soft handover, with between 40% and 75% of users being in handover with a threshold value, $\Delta_{Thresh} = 4$dB. The shadowing component, however, seems to have a lesser influence on this data, providing smaller variations in the statistics.

It is also interesting to note the number of available base stations to which users are connected during handover as the path loss exponent values are varied. There exists a marked increase in users connecting to three base stations, rather than two, as the threshold value is increased. Changing the free-space path loss exponent of $\alpha = 2$ to a value of $\alpha = 4$ providing an increase in the proportion of users connected to three base stations changing from 30% to 40%. This has an important implication for the signalling overheads which this system would incur, as one call and all associated information would then be carried three times within the same network. Although it has been commented previously with respect to the signalling load [19] that the impact of soft handover is expected to be no greater than the requirements of the current GSM hard handover strategy. However, this will not be truly justified until a full system protocol is planned and tested.

Power control was not a consideration for this analytical study, other than a simple division of power to each mobile from the base station on the downlink. However, with so many users connected to at least two base stations, it is clear that the uplink power control scheme is likely to be of extreme importance, if the near-far effect is to be avoided (Section 3.2.2.2).

Figures 3.10 and 3.11 show examples of the C/I cumulative distribution functions (cdf's) for both hard and soft handover respectively. The parameters used for these examples were: a cell capacity of $N_{Users} = 23$, shadowing component $\sigma_{log} = 8$dB and the path loss exponent $\alpha = 4$.

The system capacity was estimated from the cdf's, assuming the following system parameters: $(E_b/N_0)_{Req}$ = 5dB, outage probability of 1% and processing gain, $G_p = 156.25$. Using Equation 3.28 this gives a signal-to-noise requirement of $\gamma' = -16.9dB$. Figures 3.13 to 3.14 show the results for the shadowing environments of σ_{log} = 0dB, 8dB and 12dB respectively, each with the path loss exponent variations α = 2, 3, 4.

The simulation was developed to compare the trends in the performance of soft handover with that of hard handover with the variation in the handover threshold used. As can be seen from the results, for soft handover there is an initial system capacity gain as this threshold value is increased. Assuming the effects of signal loading within the network to be unrestrictive on this capacity, the system is optimised with a threshold value set in the range $4 \leq \Delta_{Thresh} \leq$ 6dB for each of the shadowing environments simulated. It is also worth noting that the simulated capacity at Δ_{Thresh} = 8dB still exceeds that given for small threshold values (i.e. $\leq$ 2dB) for all path loss models examined. Examination of the peak capacity with variation in shadowing component and path loss is summarised in Table 3.3. The overall trend is to decrease capacity with decreasing path loss exponent, though some erratic behaviour may exist in the results, due to the low number of iterations performed.

This common trend in capacity, throughout the studies, proves a very useful result as the propagation characteristics of any environment cannot be controlled, implying that soft handover can provide a consistent system performance improvement.

	$\sigma_{log} = 0dB$	$\sigma_{log} = 8dB$	$\sigma_{log} = 12dB$
$\alpha = 4$	33	23	22
$\alpha = 3$	24	17	18
$\alpha = 2$	13	12	16

Table 3.3: Simulated Peak Capacity for Soft Handover (Users/Cell)

Comparison of the results with previous studies proves interesting. In the downlink analysis performed by Qualcomm [11], a capacity of 38 users was found for the channel propagation statistics: $\alpha = 4$ and $\sigma_{log} = 8dB$, using hard handover with a threshold $\Delta_{Thresh} = 0dB$. However this estimate was made using a voice activity factor $\nu = 37.5\%$, in addition to adopting a power allocation scheme which manages to give each MS in a cell at least the C/I for adequate transmission [2]. In an attempt to emulate this estimate, Skold et al. [13], used a mathematical manipulation of the power management to achieve an approach similar to Qualcomm, though were not able to fully verify the claims made.

In the analytical study presented, a simple division of the available power was used to

[2] No information is given by this reference for the cases in which a BS cannot allocate sufficient power to achieve this minimum value for C/I for every user

provide coverage for the mobiles from the base stations and a higher value attributed to the voice activity factor than that used by [11]. As would be expected under these conditions, lower capacity estimates for the system were found.

In comparison to the results presented for soft handover, the hard handover scheme shows a steady drop in capacity as the threshold value is increased. Knowing the need for this threshold in any scheme, to prevent unwanted or unnecessary handovers, soft handover appears to be an automatic choice for cellular capacity enhancement. If hard handover is used the smallest viable handover threshold will maximise the system capacity under the scheme.

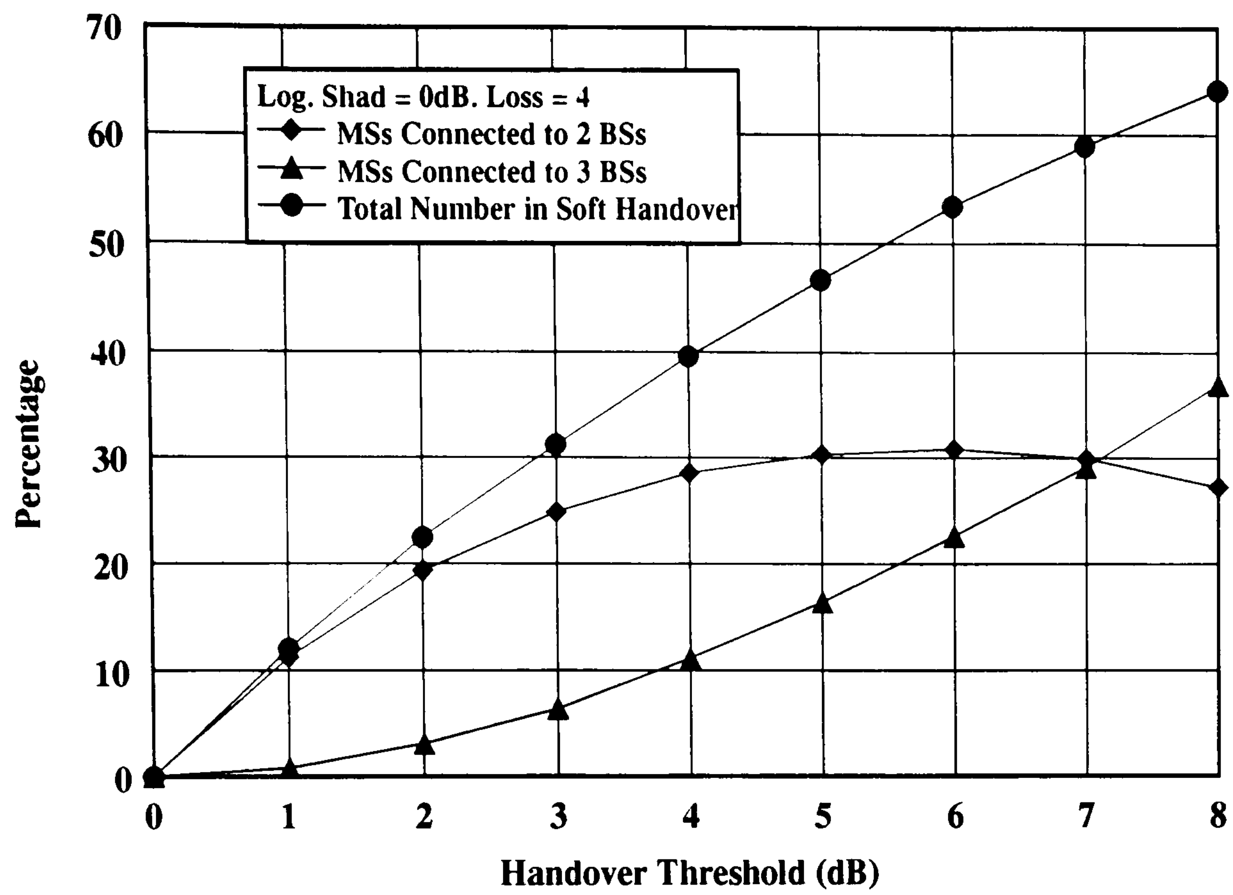

Figure 3.4: Percentage of Users in Soft Handover vs. Threshold, $\sigma_{log} = 0$, $\alpha = 4$

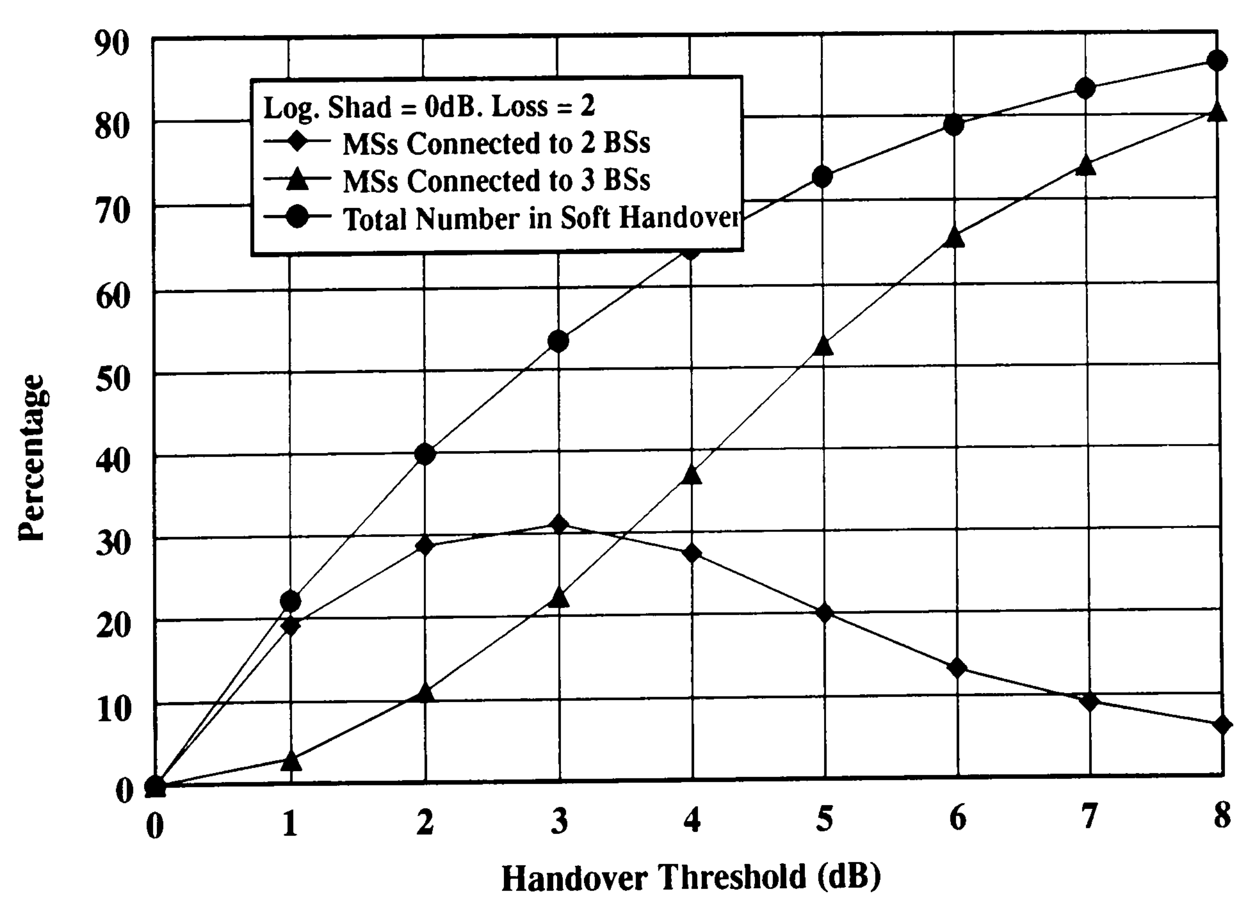

Figure 3.5: Percentage of Users in Soft Handover vs. Threshold, $\sigma_{log} = 0$, $\alpha = 2$

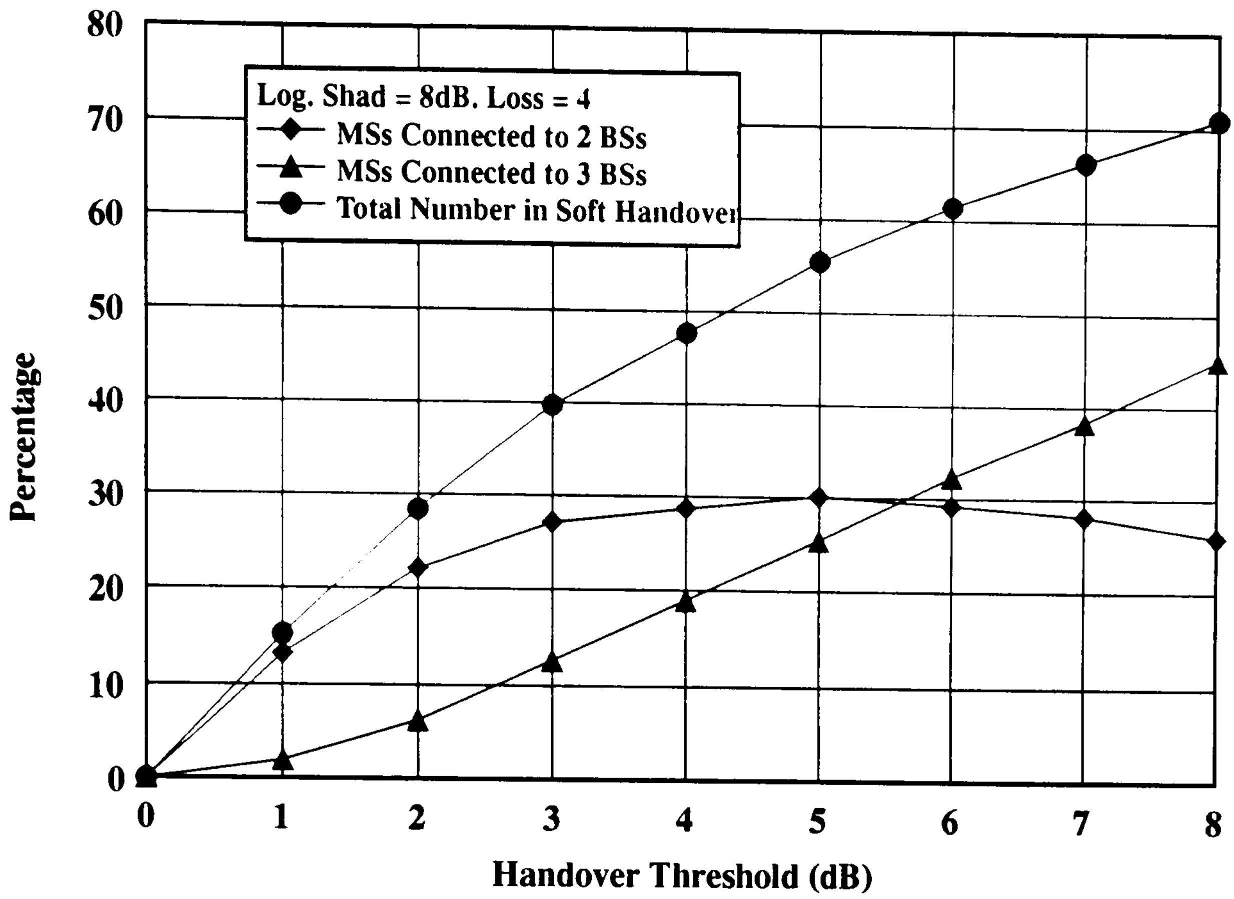

Figure 3.6: Percentage of Users in Soft Handover vs. Threshold, $\sigma_{log} = 8$, $\alpha = 4$

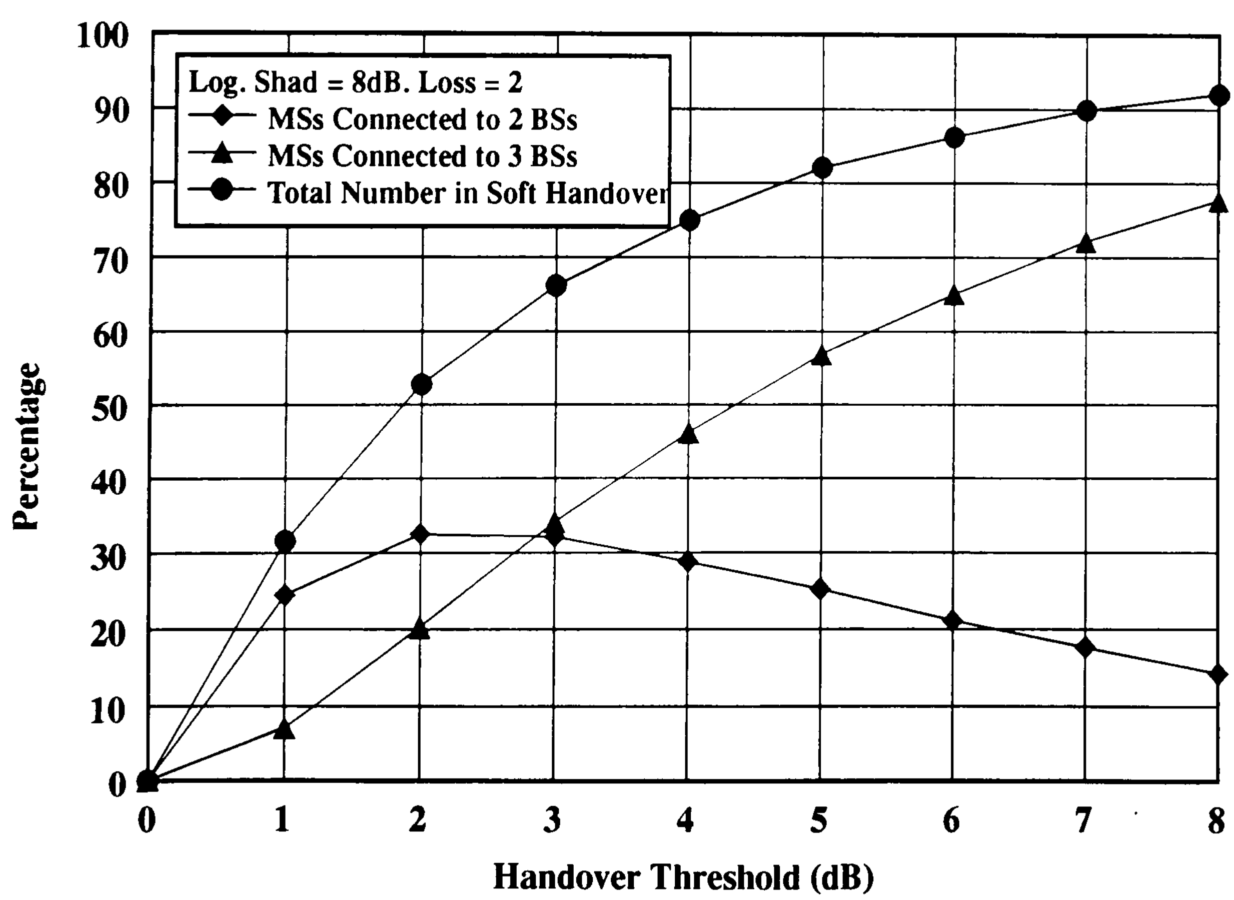

Figure 3.7: Percentage of Users in Soft Handover vs. Threshold, $\sigma_{log} = 8$, $\alpha = 2$

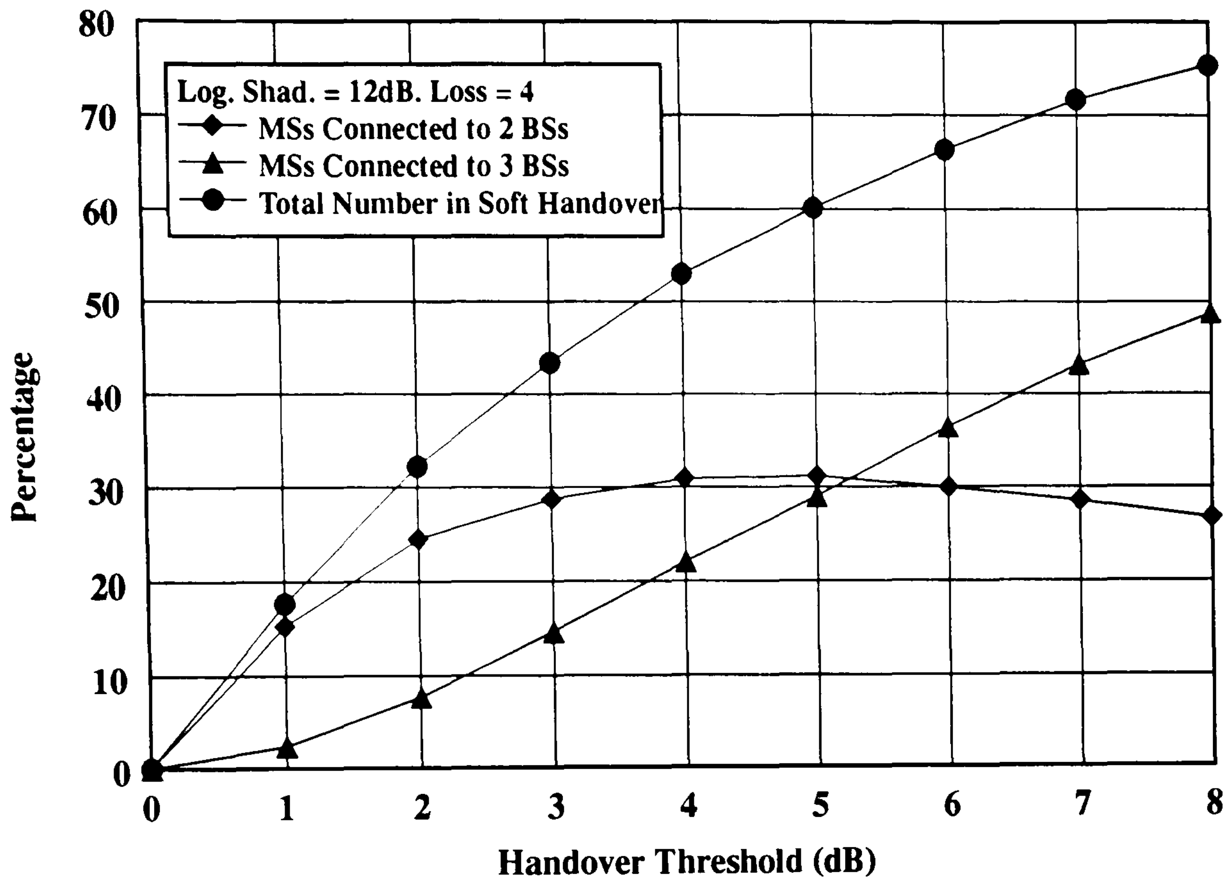

Figure 3.8: Percentage of Users in Soft Handover vs. Threshold, $\sigma_{log} = 12$, $\alpha = 4$

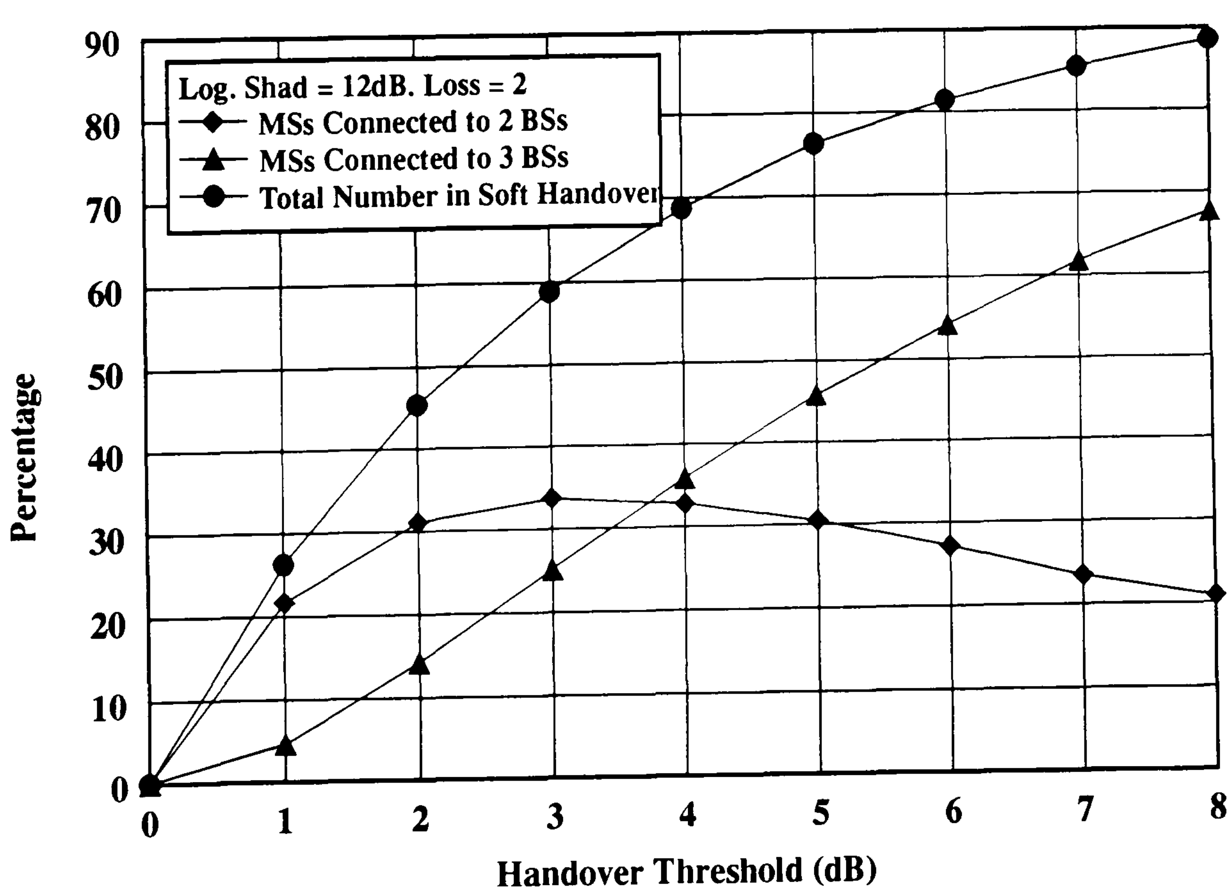

Figure 3.9: Percentage of Users in Soft Handover vs. Threshold, $\sigma_{log} = 12$, $\alpha = 2$

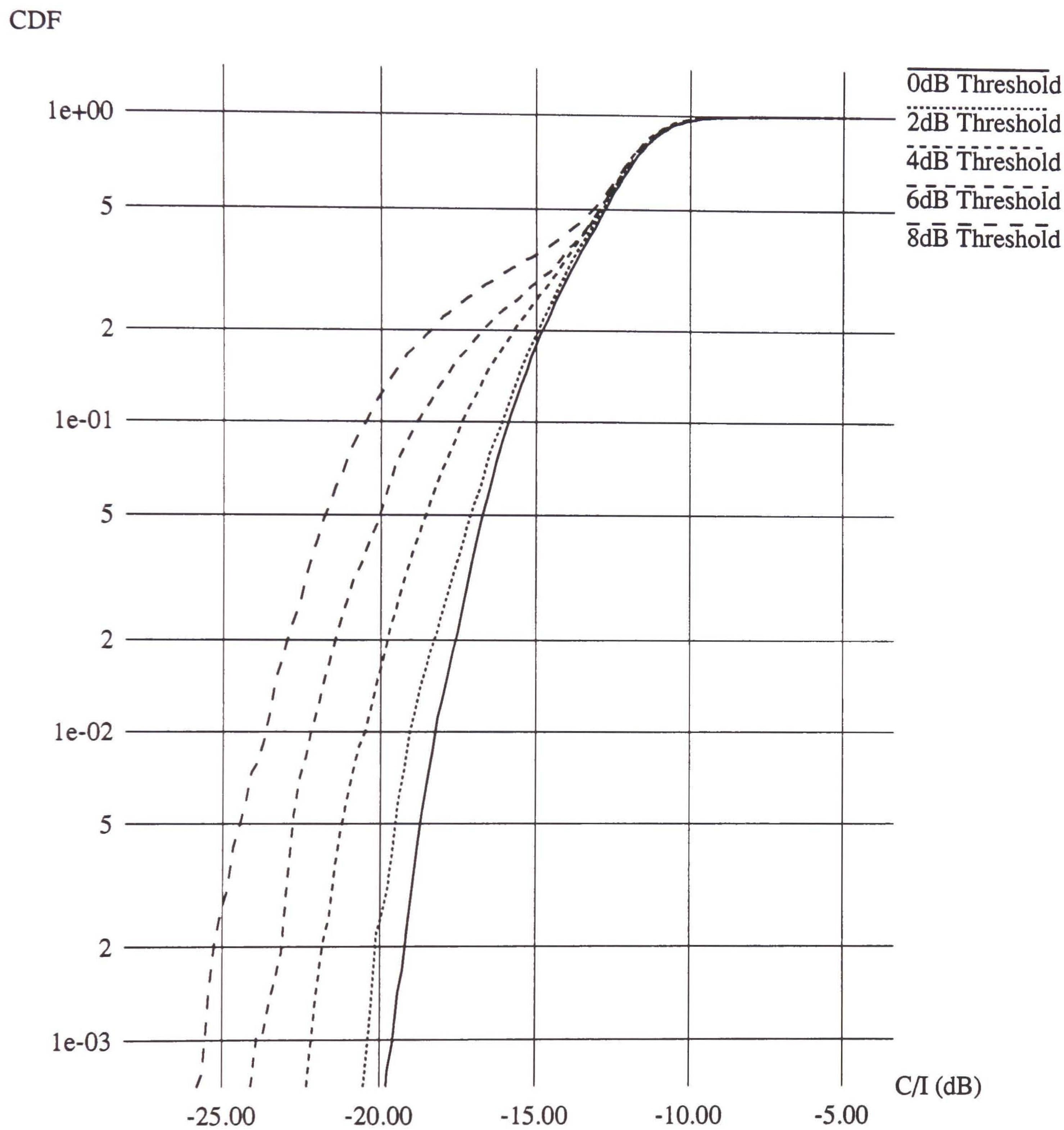

Figure 3.10: Downlink C/I distribution for Hard Handover, $N_{Users} = 23$, $\sigma_{log} = 8dB$, $\alpha = 4$

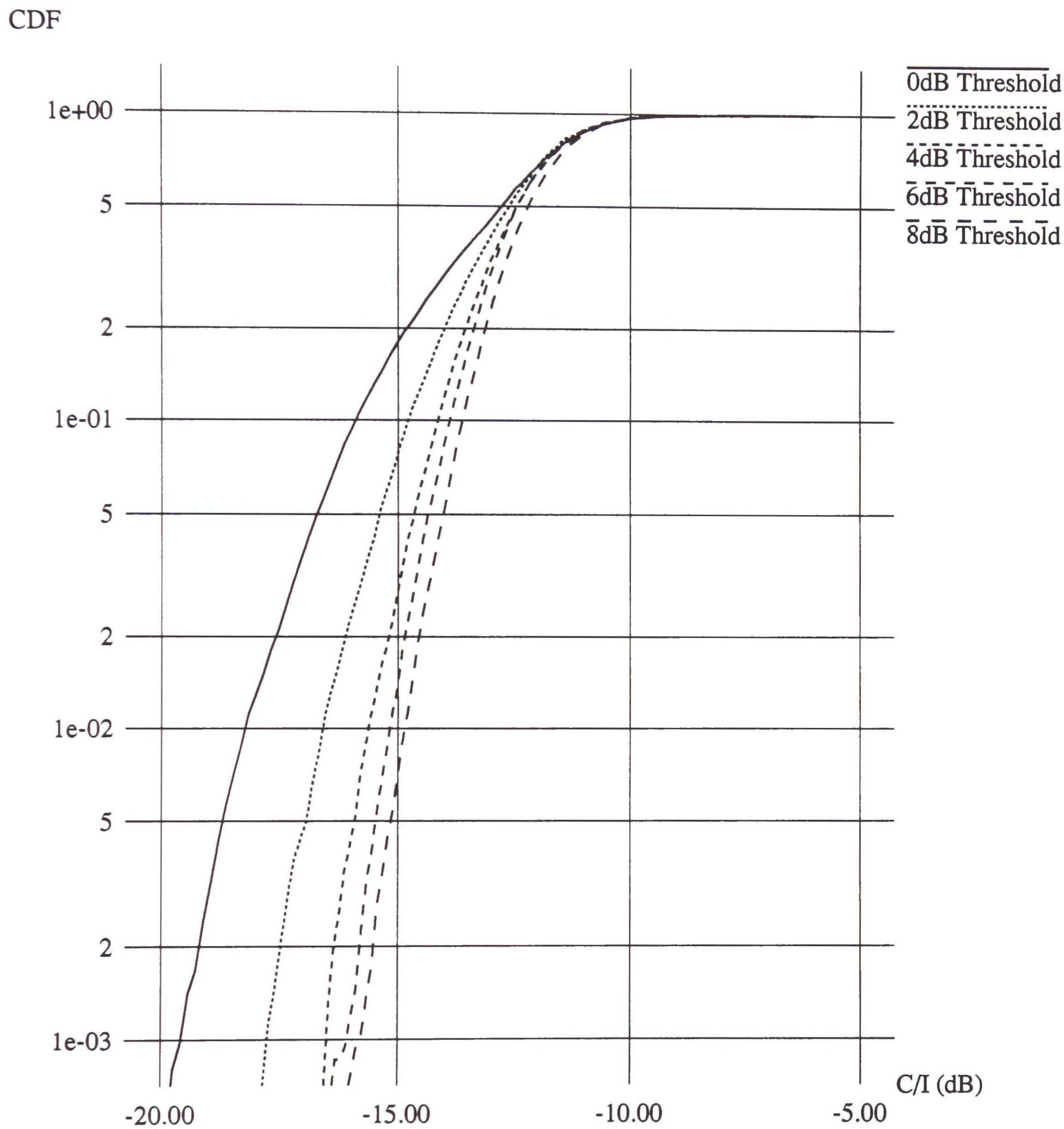

Figure 3.11: Downlink C/I distribution for Soft Handover, $N_{Users} = 23$, $\sigma_{log} = 8dB$, $\alpha = 4$

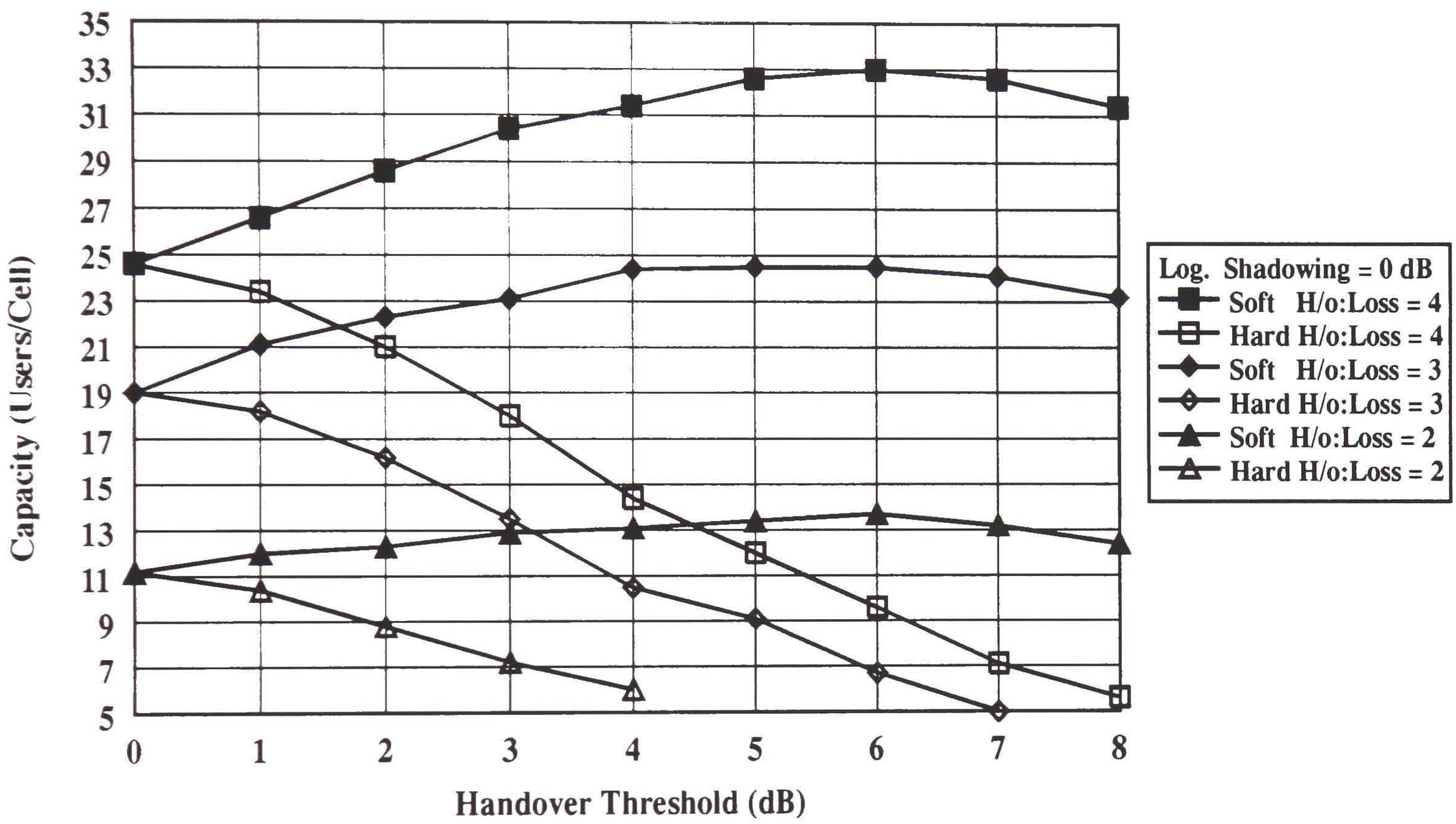

Figure 3.12: Simulated Capacity vs. Handover Threshold, $\sigma_{log} = 0dB$

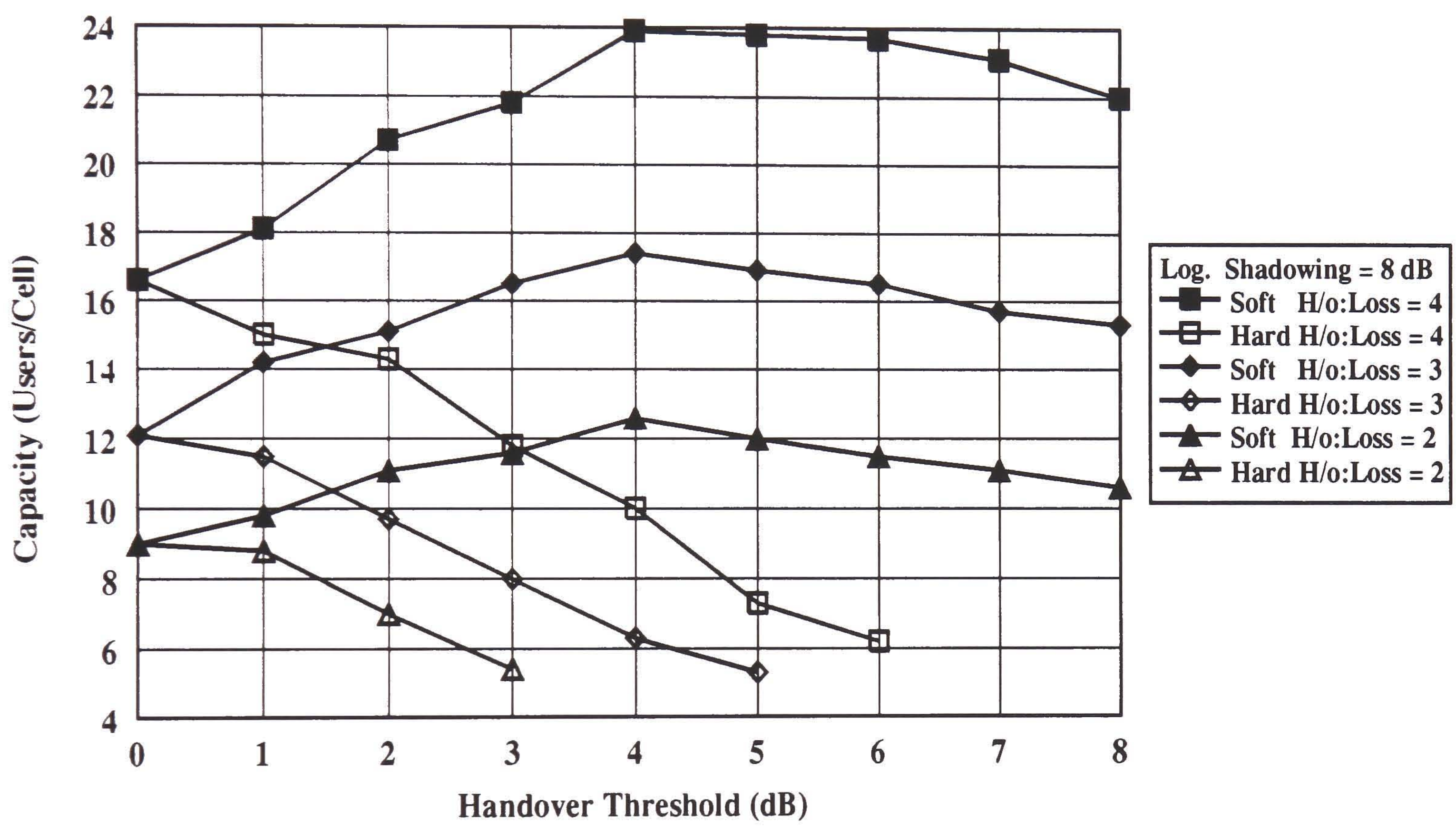

Figure 3.13: Simulated Capacity vs. Handover Threshold, $\sigma_{log} = 8dB$

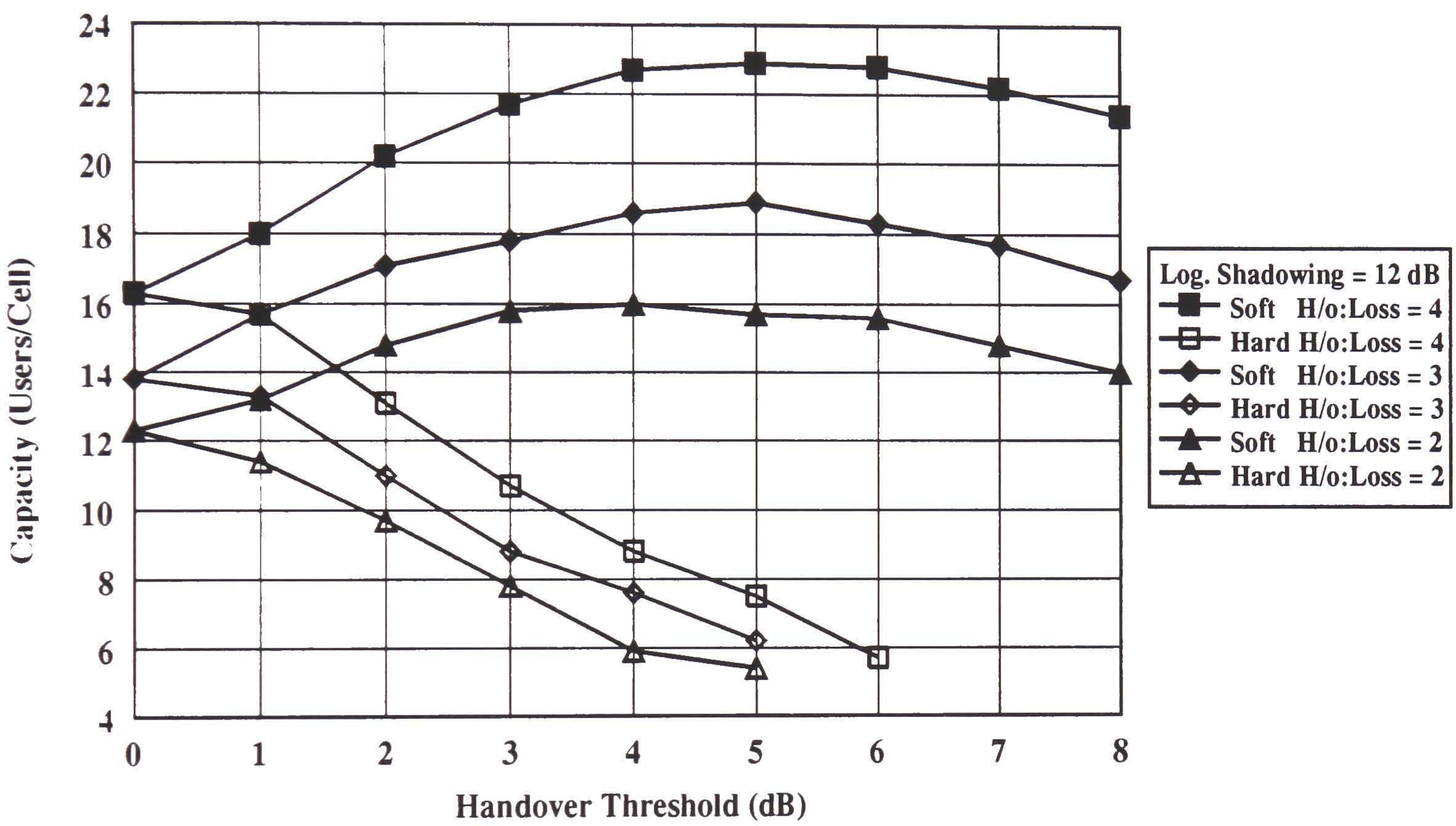

Figure 3.14: Simulated Capacity vs. Handover Threshold, $\sigma_{log} = 12dB$

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Chapter 4

Cellular Propagation Studies

> ***"For the successful implementation of microcellular systems it is essential that design tools are available which can accurately predict the coverage provided from a potential base site. This obviously relies on a fundamental understanding of the signal propagation mechanism and the resulting channel characteristics."*** - E. Green, British Telecom Technical Journal, *"Radio Link Design for Microcellular Systems"* [1]

4.1 Introduction

This chapter explains the propagation theory and channel data analysis methods used in the propagation field trials. The principles of channel sounding are explained, and a full description of the operation and performance of a purpose-built dual-channel Fast Fourier Transform (FFT) sounder system is given. The Generic Handover Algorithm, used in the analysis of the field trial data in Chapter 5, is also explained and its functionality demonstrated.

4.2 Radiowave Propagation Theory

Radiowaves can be considered as a series of transmitted rays from an antenna. Ideally, there would exist only one route or path between the transmitter and receiver system, over which the transmitted signal could travel. However, in reality there will exist a plethora of paths, resulting in multiple receptions of the same signal at the receiver, each of which will have been delayed and attenuated differently. This received signal is known as a *"multipath"* signal.

4.2.1 Attenuation

There are three principal mechanisms which can cause signal attenuation: path loss, shadowing and multipath fading.

4.2.1.1 Path Loss

The basic antenna equation gives the theoretical free-space path loss equation [2]. Consider two antennas in free space, separated by a distance r; if one antenna with a gain G_T transmits a signal with a power P_T, then the power flux density at the second, receiving antenna will be:

$$\text{Power Flux Density} = \frac{P_T G_T}{4\pi r^2} \tag{4.1}$$

The power available at the receiving antenna, P_R, is given by:

$$P_R = \frac{P_T G_T}{4\pi r^2} A \tag{4.2}$$

where A is the effective aperture of the receiving antenna, related to its power gain, G_R, by the Equation:

$$A = \frac{\lambda^2 G_R}{4\pi} \tag{4.3}$$

Substituting Equation 4.3 into Equation 4.2 gives:

$$P_R = \frac{P_T G_T \lambda^2 G}{(4\pi)^2} \tag{4.4}$$

The free space path loss, L_F, is then defined as:

$$L_F = \left(\frac{4\pi r}{\lambda}\right)^2 \tag{4.5}$$

or:

$$10\log(L_F) = 20\log(4\pi) + 20\log(r) + 20\log(\lambda) \tag{4.6}$$

where λ is the wavelength of the transmitted signal.

To simplify matters, a commonly used mean approximation to the path loss equation (Equation 4.6) is given by assuming an inverse power law for the ratio of transmitted to received signal power as a function of separation of antennas and a path loss exponent, α:

$$P_T/P_R(r,\alpha) \propto r^{-\alpha} \tag{4.7}$$

4.2.1.2 Shadowing

Shadowing or slow fading is usually due to the effects of the geographical topology, e.g. buildings, hills etc., which lead to slow changes in the local mean signal level at a mobile receiver. This effect is commonly modelled as a log-normal distribution in propagation models [3].

4.2.1.3 Multipath Fading

In any propagation environment, multipath signals are likely to be received at a receiver. With the exception of a Line-Of-Sight (LOS) path, where it exists, all the received signals will have undergone at least one of the following: reflection, refraction or diffraction. As a result, each ray will be attenuated differently and suffer from a phase-shift corresponding to its electrical length. Superposition of these rays at the receiver creates a quasi-stationary wave pattern of varying signal strength [4].

As the vehicle moves through this environment, the signal envelope fluctuates rapidly due to these multipath effects. In the case of data transmission, this may result in consecutively transmitted data symbols arriving at the receiver at the simultaneously, or at least overlapping. This form of interference is known as Inter-Symbol Interference (ISI).

However, because of the nature of operation of a DS-CDMA system, the use of a high signalling rate and hence spreading bandwidth, compared with the symbol rate, gives an inherent immunity to multipath effects [5]. Hence increasing the spreading bandwidth of the system and so increasing the processing gain (Section 2.6.3.3), allows better differentiation between adjacent transmitted symbols.

4.3 Diversity Combining Techniques

In a multipath fading environment, uncorrelated signals can be received at separate antennas and selected/combined such that the resultant received signal will have an improved performance over a single antenna system. Figure 4.1 illustrates the diversity reception principle for M separate antennas used in a receiver system.

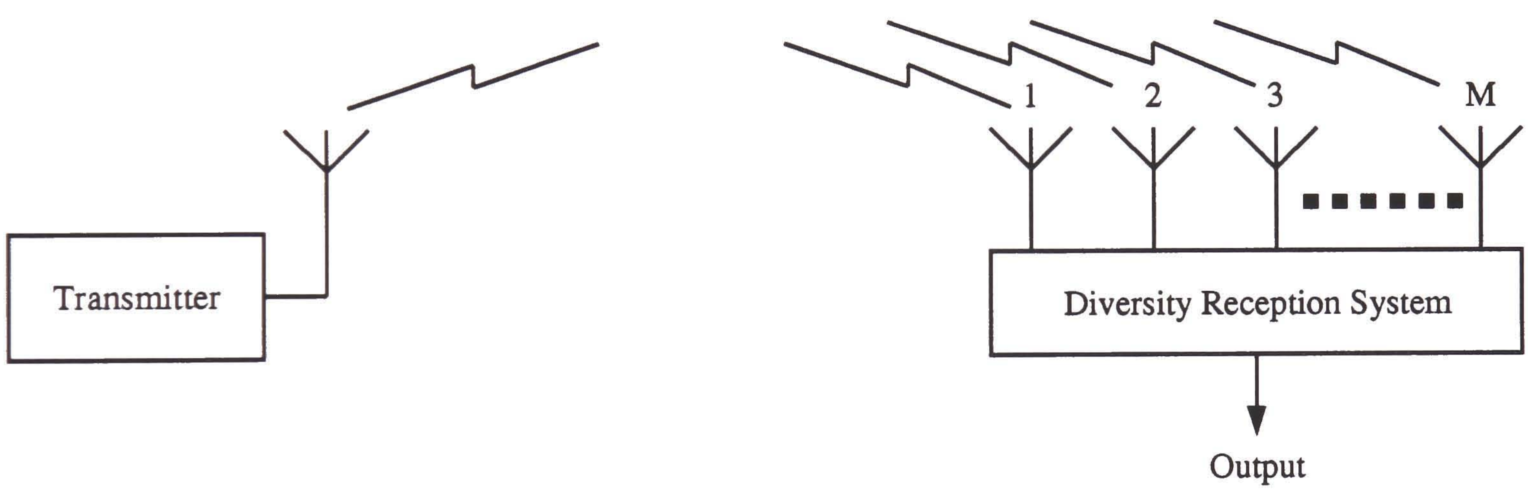

Figure 4.1: Principles of Diversity Reception

4.3.1 Selection/Switched Diversity

Selection diversity is the simplest of the diversity technique. With reference to Figure 4.1, the signal-to-noise ratio (SNR) from each of the M receiver antennas is measured and the highest SNR is *selected* to be used as the output. Simulated results from a system incorporating this form of diversity can give potential savings of 10dB in the case of two-branch diversity, at the 99% reliability level and 16dB for four branches, over a single reception antenna system [6].

4.3.2 Scanning Diversity

Scanning diversity is a similar technique to selection diversity except the antennas are *scanned* in a set sequence until one is found which can supply a SNR above a set threshold. This antenna is then used for reception until the SNR falls below the minimum required level. However, this technique will give an inferior performance in a fading environment to the other diversity techniques [6].

4.3.3 Maximal Ratio Combining

The Maximal Ratio Combining (MRC) technique uses all M diversity received signals to form a single output [6]. For the combining process each signal must first be co-phased and then given a weighting proportional to its signal voltage to noise power ratios, before summing together.

If the received signal envelope at the ith antenna is s_i, then the combined signal envelope, s, can be expressed as:

$$s = \sum_{i=1}^{M} a_i s_i \tag{4.8}$$

where the signal weighting a_i is given by:

$$a_i = \frac{\text{Received Signal Voltage at Antenna } i}{\text{Received Noise Power at Antenna } i} \tag{4.9}$$

The total received noise power from all branches, N_T can be expressed as the sum of the noise powers, $\bar{n}_i^2$, from each branch weighted by the branch gain factor:

$$N_T = \sum_{i=1}^{M} \bar{n}_i^2 a_i^2 \tag{4.10}$$

The resultant SNR of the combined signal, γ_R, is:

$$\gamma_R = \frac{s^2}{2N_T} \tag{4.11}$$

If a_i is chosen such that $a_i = s_i/\bar{n}_i^2$ then γ_R is maximised with the value:

$$\gamma_R = \frac{\left(\sum_{i=1}^{M} s_i^2/\bar{n}_i^2\right)^2}{2\sum_{i=1}^{M} \left(s_i/\bar{n}_i^2\right)^2} = \sum_{i=1}^{M} \frac{s_i^2}{2\bar{n}_i^2} = \sum_{i=1}^{M} \gamma_i \tag{4.12}$$

Thus the SNR of the resultant signal is equal to the sum of the individual branch SNRs.

This technique can be shown to give the best statistical reduction in fading of any linear diversity combining method : two branch MRC gives 11.5dB gain at the 99% reliability level and four branch combining gives a gain of 19dB. these are signal strength improvements of 1.5dB and 3dB respectively over simple selection diversity (Section 4.3.1).

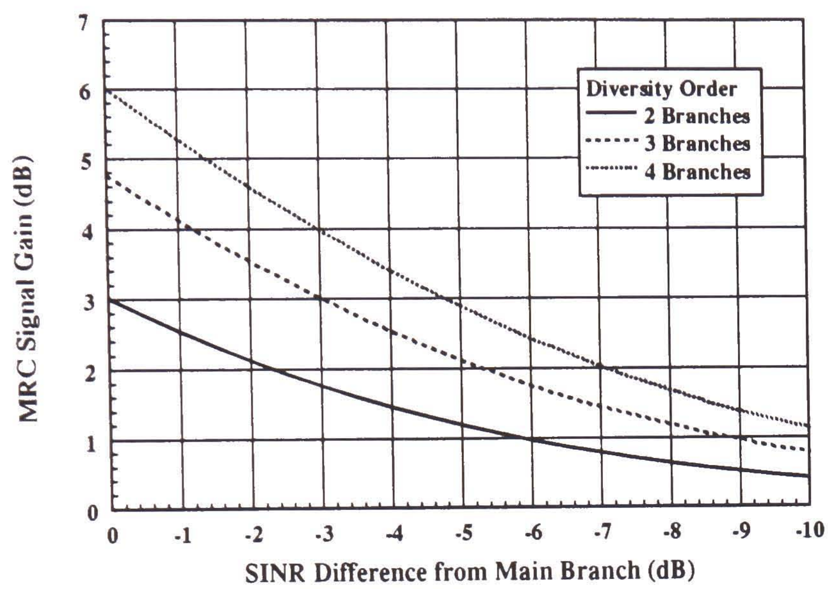

Figure 4.2: Maximal Ratio Combining of Signals below main Branch Power

4.3.3.1 Equal-Gain Combining

Equal gain combining differs from MRC in that all the weighting coefficients, a_i, are set equal to one [6]. The combined signal envelope can then be expressed by:

$$s = \sum_{i=1}^{M} s_i \tag{4.13}$$

and the SNR

$$\gamma_E = \frac{s^2}{2NM} \tag{4.14}$$

again assuming the signal noise power in each branch $\bar{n}_i^2 = N \ \forall\ i$.

The performance of equal gain combining can be shown to lie between that of MRC and selection diversity.

4.4 Wideband Channel Estimation

A *"wideband"* communications system is one in which the operating bandwidth has a value greater than the coherence bandwidth. The coherence bandwidth being defined as the frequency separation at which the amplitude correlation of a signal has the value 0.9 [2]. Any system operating at frequency bandwidth less than the coherence bandwidth is termed *"narrowband"*.

The spreading bandwidth of a DS-CDMA system is an important consideration in respect of its performance in a multipath environment (Section 4.2.1.3). Loss of signal quality due to fading is an important aspect of the system design. Narrowband systems are inherently more susceptible to multipath fading than wider-band systems, which can actively utilise the individual fading components, for example through RAKE combining [7]. In a demonstration wideband system developed by Schilling et al. [8], typical worst-case losses due to multipath fading were found to be approximately 2dB, for a a system with a spread spectrum bandwidth of 48MHz and information bandwidth of 32kHz. Whereas for a narrowband system, with a bandwidth of only 1MHz, fading losses would be expected to exceed 10dB to 30dB.

A large spreading bandwidth also enables the system to carry high-rate data traffic, as is required by some aspects of UMTS and MBS. With data rates proposed for DS-CDMA in excess of 5MChips/s [9], investigations into the propagation statistics of these wideband channels are required to estimate the signal behaviour during handover.

There are two main methods for wideband channel estimation [10] :

1. Pulsed Transmission. A pulsed transmission channel sounder uses envelope detection of a short transmitted pulse of Radio Frequency (RF) energy to estimate a channel impulse response.
2. Pseudo-Random Binary Sequence (PRBS) Sounding. A continuous transmitted *"noise-like"* sequence is transmitted. Correlation of this sequence after transmission gives the channel impulse response.

Both methods provide an estimate of the Channel Impulse Response (CIR), with the level of estimation determined by the equivalent sounding pulse width and the linearity of the system [2].

However, in comparison, the pulse sounding technique has no readily available reference if absolute time delays are required. It also requires a more linear amplification technique in order to maintain pulse shape. It has a more limited range to PRBS for a set power output and the resolution of the pulse after transmission is determined more by the storage equipment rather than the configuration of the sounder. In addition, unlike Pulsed sounding, PRBS sounding can differentiate between the base stations at the receiver unit if unique pseudo-noise (PN) codes are used in each transmitter. Therefore, PRBS sounding is chosen over Pulsed Transmission for channel estimation of the signals received from two base stations for the handover experiments described in this Thesis.

4.5 Pseudo-Random Spreading Sequences

The spreading codes used are selected to have certain properties which make them suitable for use in Spread Spectrum communications systems. These properties include:

- The auto-correlation function of the spreading code (a comparison of the code with a delayed version of itself), should be only two-valued, to allow initial acquisition at the receiver and long-term tracking.
- The transmitted spread signal is likely to use a very wide bandwidth, so a simple code generator is required which can operate at a high frequency or *"chipping rate"*.
- For multiple access communications, a set of spreading codes is required which have good cross-correlation properties (i.e. all other codes will appear as noise to a desired user's code) [11].
- For secrecy and to combat noise or intentional jamming, the spreading waveform should have a long period. For long codes it is possible to model them as Gaussian noise sources [12]
- 'Noise-like' appearance - code lengths are usually very long, have no repetition within the code and one more '1' than '0' which makes them appear to be similar to white noise.
- Low cross-correlation coefficients - hence the presence of another code (or in-band user) effectively acts as additional white noise and will not be de-spread at the receiver.

Common code types used are "Maximal length sequences" or m-sequences. These are easily generated from shift registers e.g. a shift register of length 7 can be used to generate 18 unique pseudo-random sequences. By modulo-2 combination of the outputs of these shift registers it is possible to produce "preferred pair" codes or "Gold Codes" [13] [14] which have very good auto-correlation and cross-correlation properties. Hence use of these preferred pair codes in the channel sounder system give a good channel impulse response, with minimal co-channel interference.

However, in a quasi-synchronous DS-CDMA system, it is possible to re-use the same sequence for modulation, using different time-offsets of the code to separate the users [15].

Further information on the theory of spreading sequences may be found in [16] [17] [18].

4.5.1 PRBS Sequences in Channel Estimation

The channel characteristics between two adjacent base stations, in particular, the handover area will be measured by a dual-channel sounder. The sounder operates by simultaneously logging the bi-phase modulated PN signals transmitted from both base stations with a dual-channel receiver. Both base stations transmit at the same nominal carrier frequency, but they are differentiated by distinct PN codes. The codes are selected to give good auto-correlation and cross-correlation properties. For an N-bit bi-phase modulated sequence of +1 and -1, the chosen sequence gives a peak of N units when the sequence aligns with a replica of itself. When there is an offset between the sequence and its replica, the correlation is -1. Mathematically, the auto-correlation function of the sequence can be expressed as:

$$R_{xx}(\tau) = \begin{cases} N & \text{if } \tau = 0 \\ -1 & \text{otherwise} \end{cases} \tag{4.15}$$

In order to differentiate between base stations in the field trials, the PN codes are chosen to give low cross-correlation. They are called preferred pair PN codes. The magnitude of the cross-correlation function of the preferred pair codes can be expressed as:

$$|R_{xy}| \leq 2^{\lceil (n+1)/2 \rceil} + 1 \tag{4.16}$$

where $\lceil x \rceil$ denotes the nearest integer larger than x. The channel impulse response (CIR) between the transmitter and the receiver is measured by correlating the received signal and a replica of the transmitted PN code. The received signal consists of the modulated PN code distorted by the channel, noise and interference from the other transmitter. Therefore, the received signal can be expressed as:

$$r(t) = s(t)h(t) + n(t) + s_1(t)h_1(t) \tag{4.17}$$

where $s(t)$ is the transmitted PN code from the wanted base station, $n(t)$ is noise and $s_1(t)$ is the PN code from the adjacent base station, while $h(t)$ and $h_1(t)$ are the CIR for the wanted base station and the adjacent base station, respectively. At the receiver, the estimated CIR for the wanted base station can be expressed as:

$$\hat{h}(t) = R_{xx}h(t) + s(t)n(t) + R_{xy}(t)h_1(t) \tag{4.18}$$

Therefore, the estimated CIR contains the actual CIR dispersed by the auto correlation of the PN code as in the first term of Equation 4.18, while the latter two terms represent the noise and interference components. Consequently, the accuracy of the estimated CIR can be improved by using a longer sequence which gives a higher and narrower peak for $R_{xx}(t)$, in addition to choosing a preferred pair of sequence that gives lower $R_{xy}(t)$.

4.6 Channel Sounder System Overview

The FFT channel sounder system operates at a centre frequency of 1823MHz, close to the Future Public Land Mobile Telecommunications System (FPLMTS) allocated frequency band (1885MHz to 2025MHZ). The FFT channel sounder was initially developed under RACE PLATON [19] specifically to develop an understanding of soft handover and methods of optimisation of the soft handover process.

Figure 4.3 shows the measurement system used for the diversity handover field trials. It comprises two base station transmitters and one Fast Fourier Transform (FFT) dual-channel mobile receiver [20]. The two base stations are used to provide adjacent microcellular coverage regions with an overlap of coverage or potential handover region. The receiver system is capable of simultaneously receiving and distinguishing the transmitted signals from either of the base station transmitters as it is driven about the study environment along a specified route. It is also capable of logging its relative position in the environment with the received data.

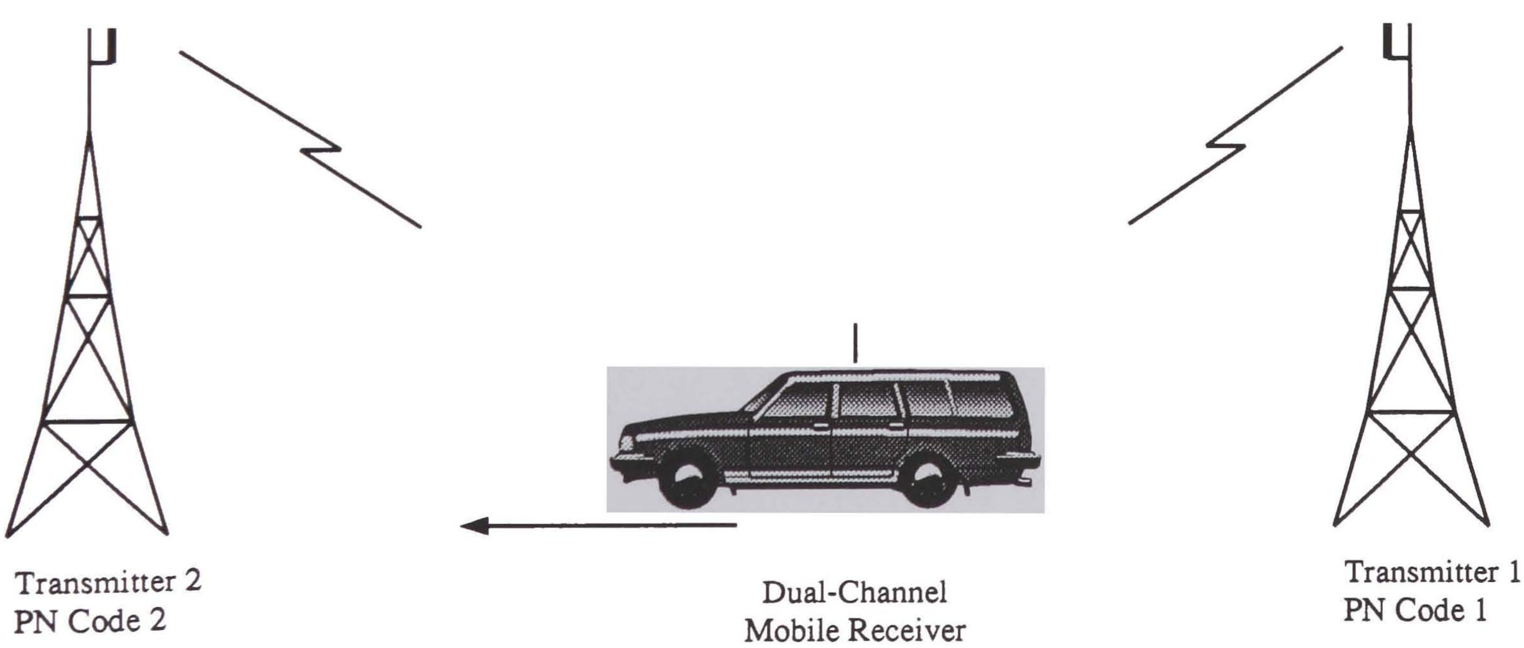

Figure 4.3: Diversity Field Trial Setup

4.6.1 Base Station Transmitters

A photograph of one of the base station transmitter units is shown in Figure 4.4 and a simplified block diagram of the unit shown in Figure 4.5. The transmitters use an 160MHz signal to bi-phase modulate a 511 bit PN binary code. The PN code is clocked or *"chipped"* at 8Mchips/s.

The length and chipping rate of the PN sequence determine three of the system parameters: the echo resolution, the maximum path length observable and the theoretical peak-to-noise ratio of the received response. The echo resolution of the sounder is given by the bit interval of the sequence which is 125ns - an equivalent path distance of about 37 metres. The maximum path length is given by the echo resolution multiplied by the sequence length:

$$\text{Path Length}_{max} = 125\text{ns} \times 511\text{bits} = 63.875\mu\text{secs or } 19.149\text{km} \tag{4.19}$$

The theoretical maximum peak-to-noise ratio of the system is given by the square of the sequence length:

$$\text{Peak-to-Noise}_{max} = 261121 \text{ or } 54.17\text{dB} \tag{4.20}$$

Although in practice the maximum peak-to-noise ratio of the sounder would be reduced by the dynamic range of other components used in the sounder system e.g. mixers and filters.

The modulated PN signal is filtered through a 15MHz bandwidth Surface Acoustic Wave (SAW) device to meet licencing requirements, before up-conversion to 1823MHz. The signal is then amplified in two stages and filtered before transmission across the channel. Figure 4.6 shows the output spectrum from the transmitter.

Each base station transmitter contains identical radio frequency (RF) components. However, the codes used by each transmitter can be one of a preferred-pair of PN codes (Section 4.5) which allow the receiver system to distinguish between base stations without ambiguity. For the microcellular studies the transmitter output powers are set to similar magnitudes.

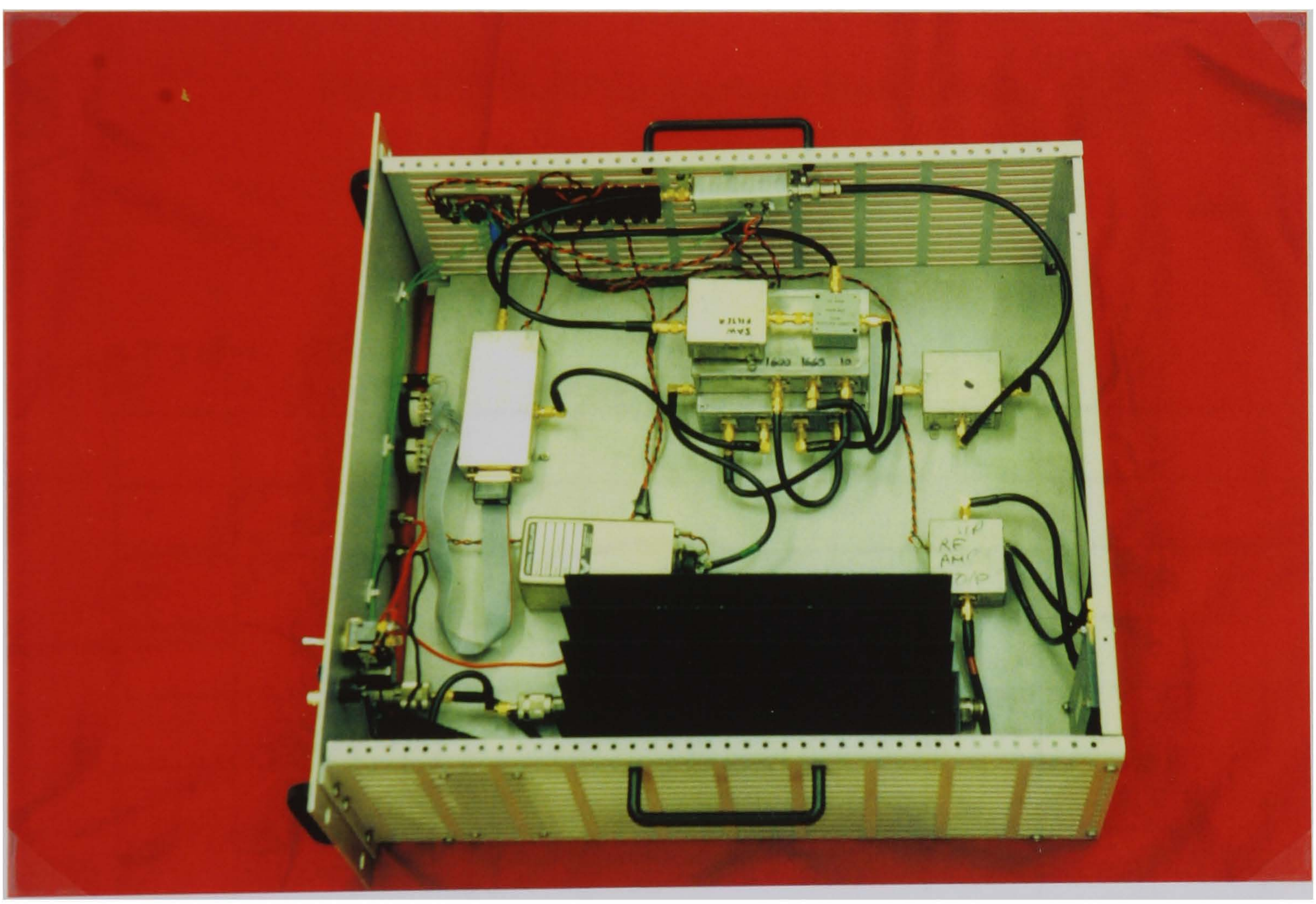

Figure 4.4: Photograph of Wideband Transmitter Unit

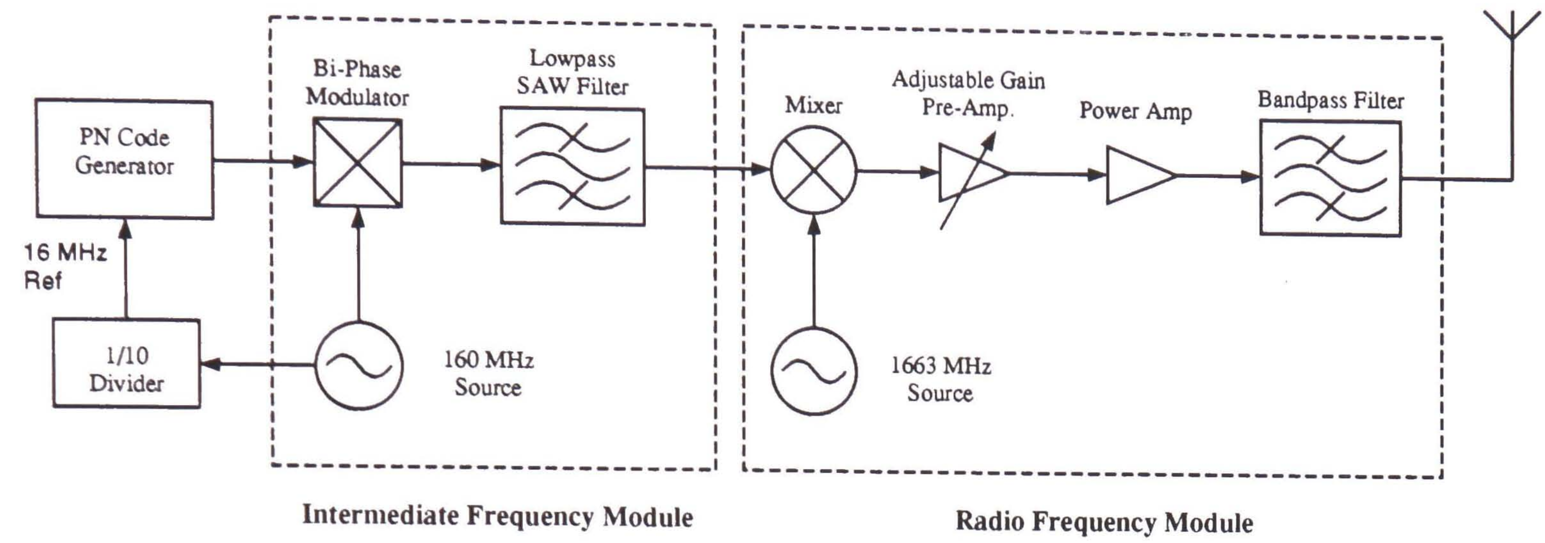

Figure 4.5: DS-CDMA Wideband Transmitter

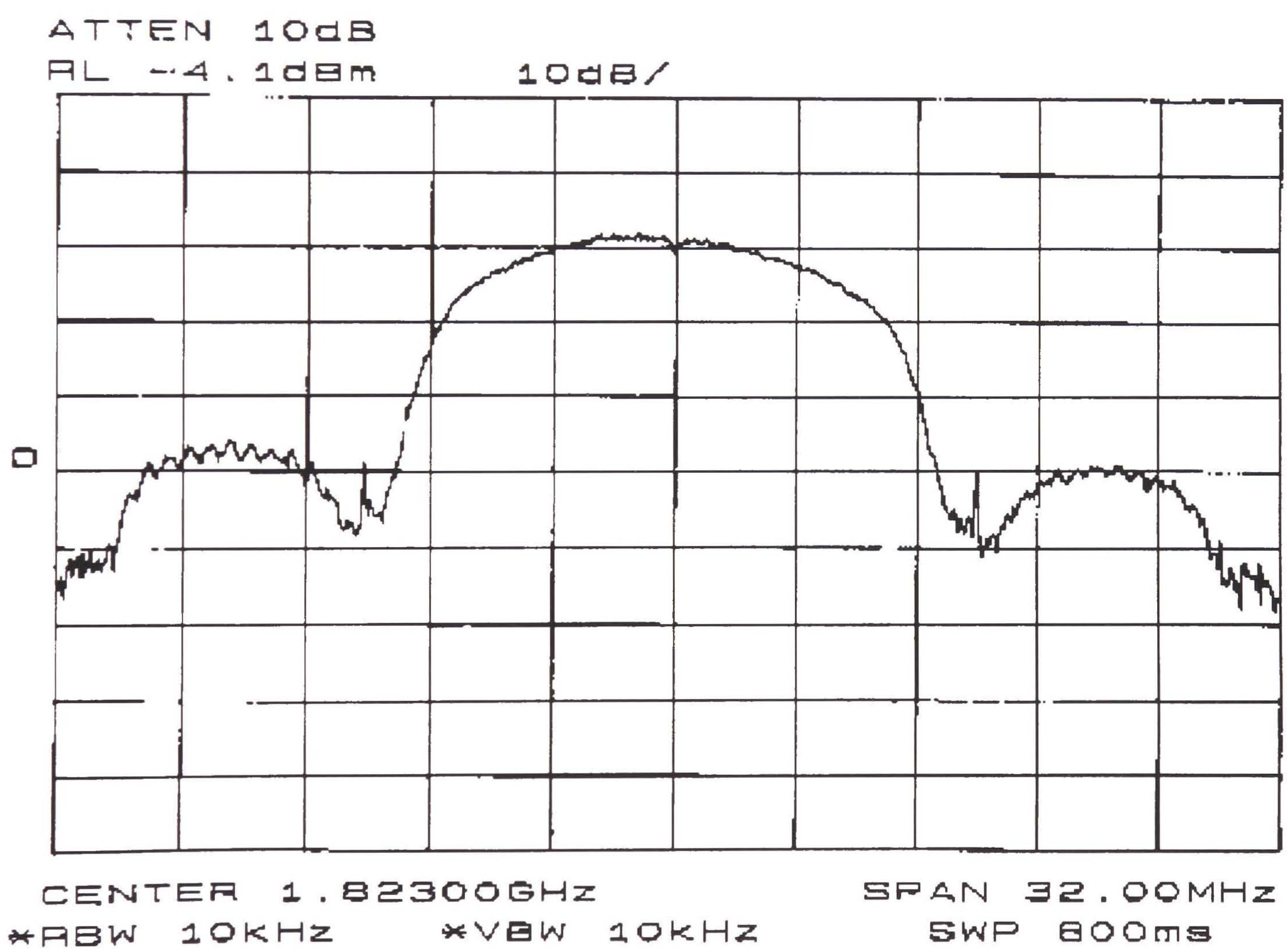

Figure 4.6: Transmitter Unit Output Signal Spectrum

4.6.2 Mobile Receiver Unit

The receiver unit down-converts the received signal to an intermediate frequency (IF) and then performs a correlation between the IF signal and stored reference PN codes. The PN sequences correspond to those used by each of the base station transmitters and are used to distinguish between the channel impulse responses (CIRs).

The receiver comprises three functional units: a radio frequency (RF) module, a data processing module (DPM) and a personal computer (PC). A simplified block diagram of the receiver is shown in Figure 4.7.

The RF module architecture is shown in Figure 4.8. The received signal is first filtered and amplified before down-conversion to an 160MHz IF. The down-conversion process is performed by mixing the received signal with a 1663MHz PLL-generated waveform. The IF signal is then filtered using a 12MHz bandwidth SAW filter and amplified before passing onto the DPM module.

The DPM module sub-samples the IF signal with an analogue-to-digital converter (ADC) at 128MHz, producing a signal image centred at 32MHz. The Digital Signal Processing (DSP) module digitally mixes down, filters and decimates the 32MHz signal, to produce a baseband quadrature signal. Filtering and decimation are carried out to reduce the length of the subsequent FFT operation and the data storage requirements. Correlation of this signal can then be performed within the DSP module with a reference PN code for each of the transmitters, using Fast Fourier Transform techniques [21]. The operations of the FFT blocks in the DSP module are shown in Figure 4.9.

Control of the FFT sounder, data transfer and storage are via a PC connected to the DPM module via a VMEbus. Detailed discussions of the FFT sounder modes of operations are given in Section 4.7. Figures 4.10 and 4.11 show photographs of the RF module and the combined DSP and PC units.

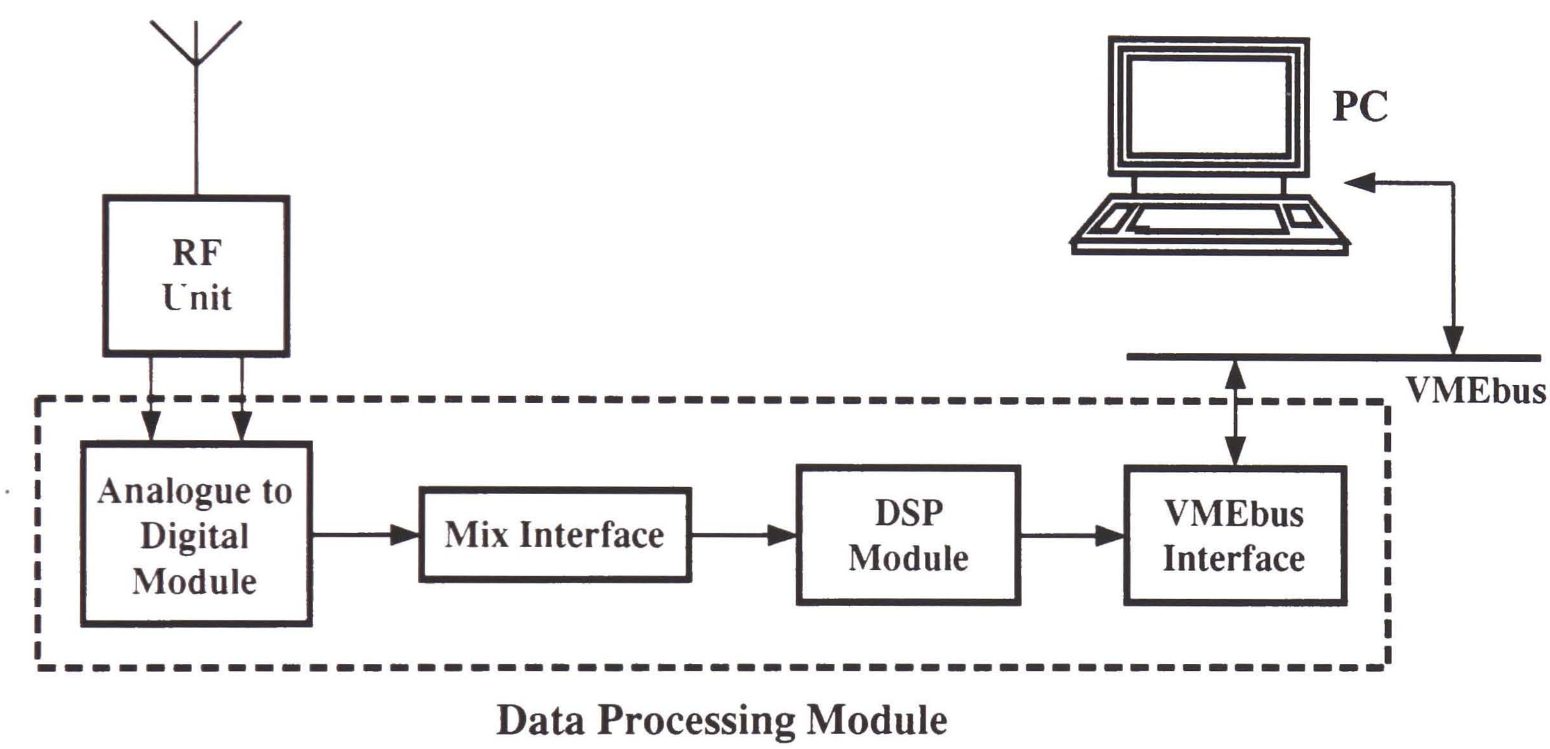

Figure 4.7: DS-CDMA Dual-Channel Receiver Block Diagram

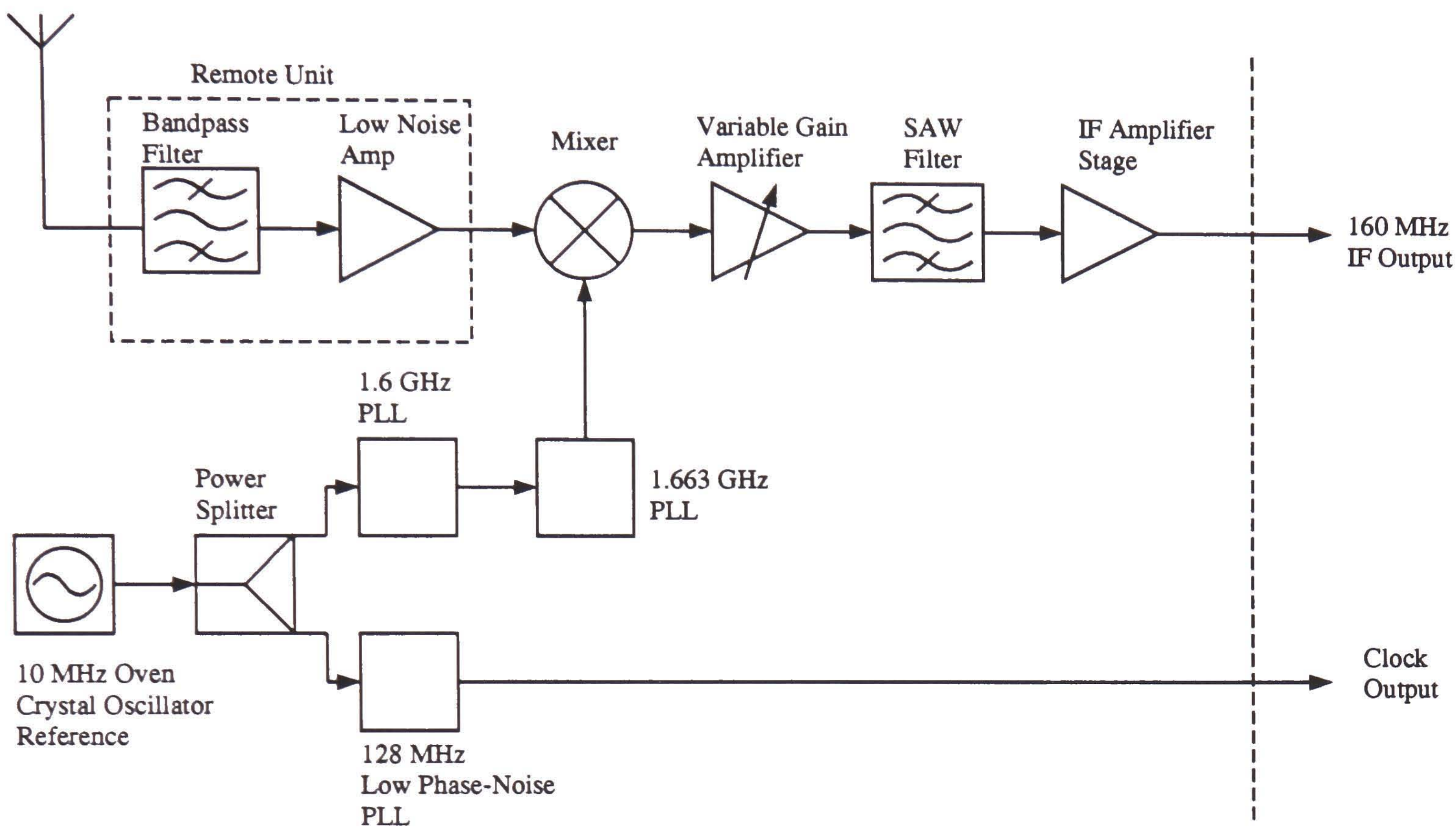

Figure 4.8: RF Module Architecture

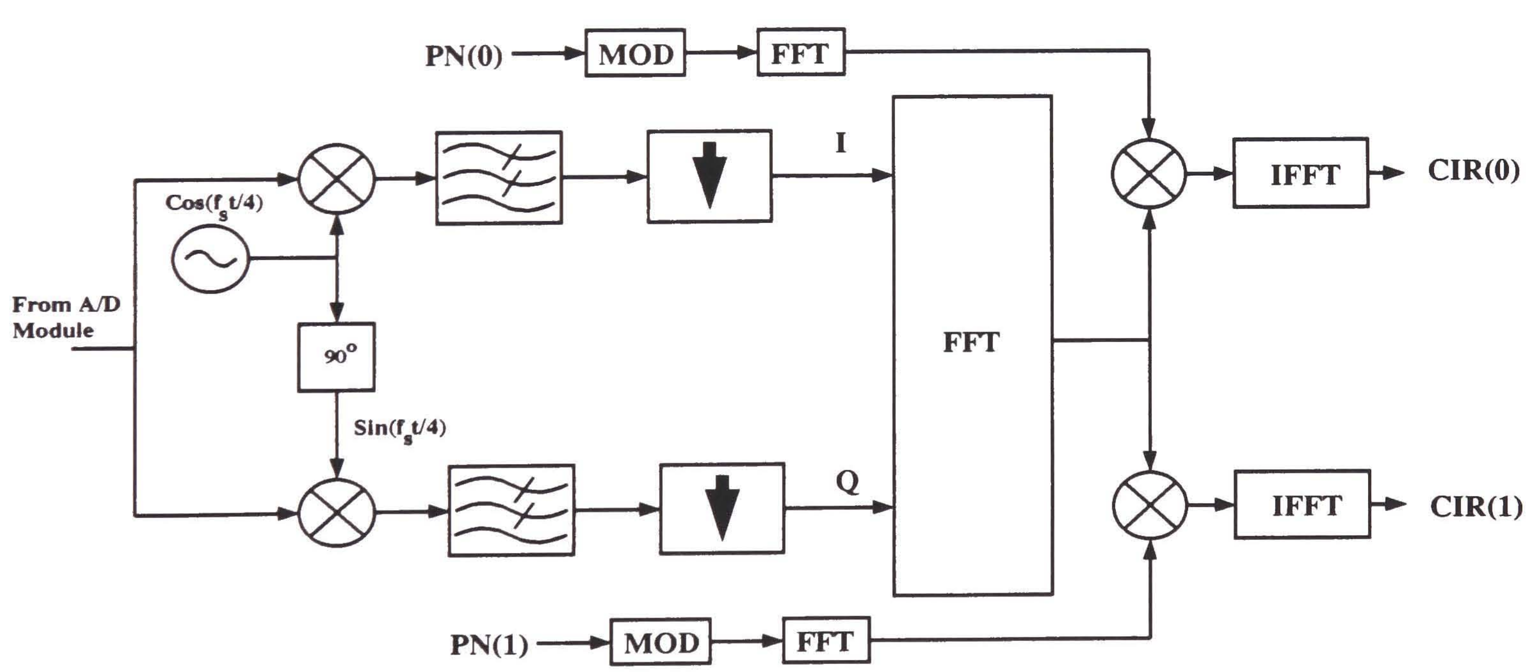

Figure 4.9: DSP Module Architecture

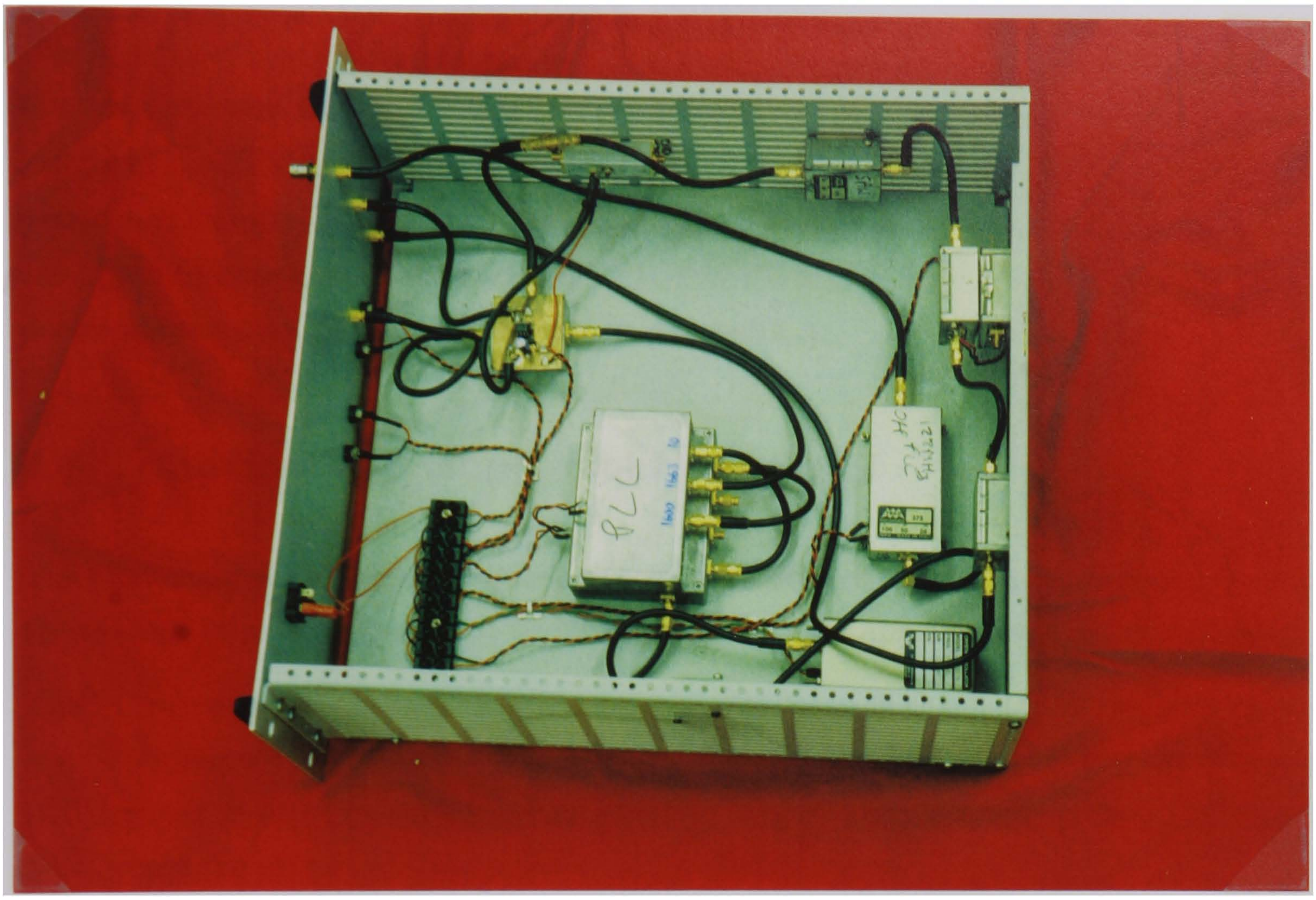

Figure 4.10: Photograph of FFT Dual-Channel Receiver RF Module

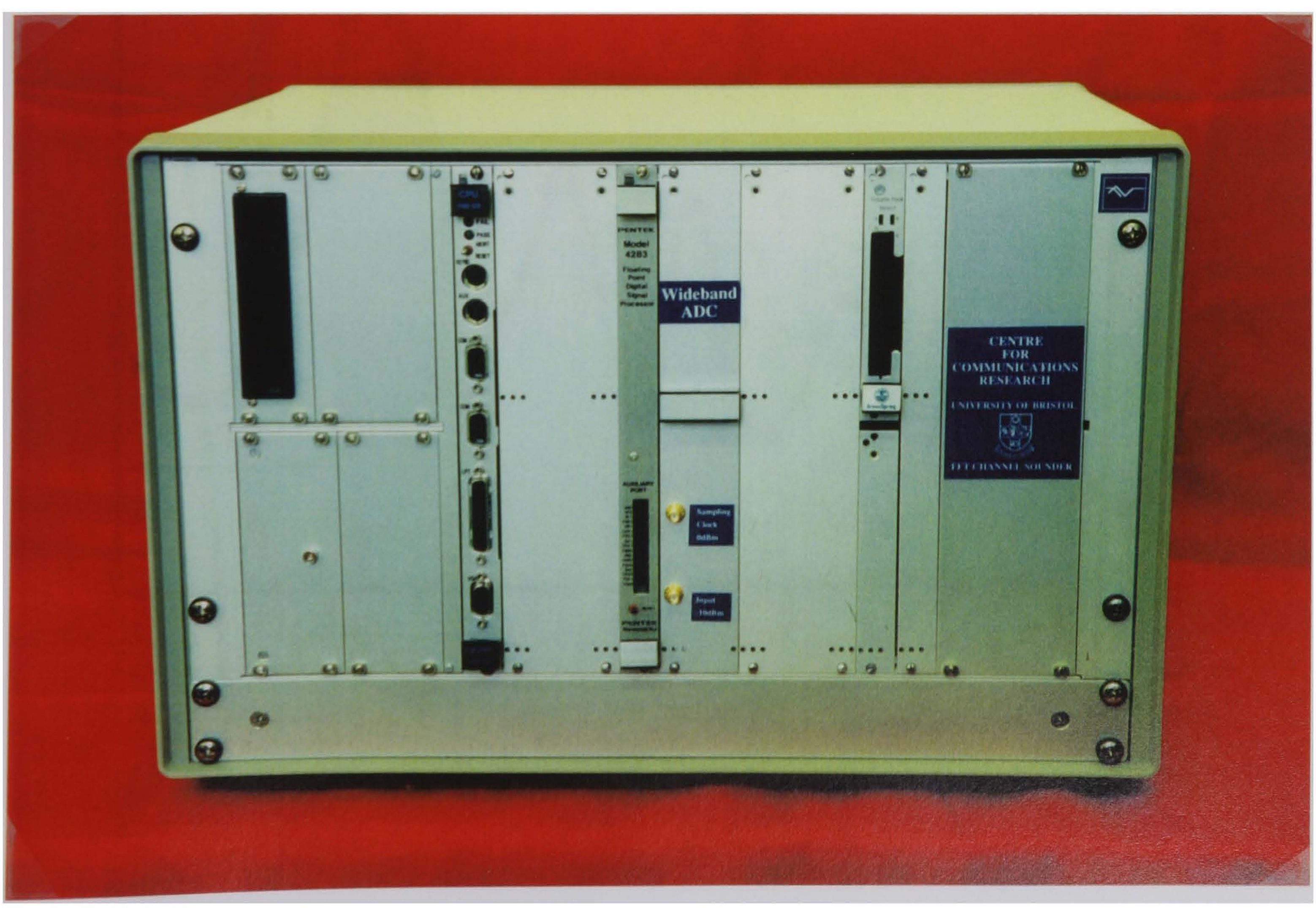

Figure 4.11: Photograph of FFT Dual Channel Receiver DSP and PC Unit

4.7 Man-Machine Interface Software

The Man-Machine Interface (MMI) software provides a menu-driven user interface for the control of the FFT dual-channel sounder receiver. It also processes data to obtain the CIR parameters. Depending on the operation mode selected by the user, the program enters one of the following modes: *STORE ONLY*, *DISPLAY ONLY* or *OFFLINE* mode. These modes of operation as discussed further in Appendix A.

4.8 Multipath Channel Characteristics

The dual-channel FFT sounder allows the characteristics of the multipath environment and the channel impulse responses to be obtained in the following manner:

The PC retrieves the channel impulse response data for each channel from the VME memory. A sliding window is then used to extract the portion of the channel impulse response (CIR) where most of its energy is concentrated. An arbitrary example is shown in Figure 4.12, where the extracted CIR is shown as the shaded region.

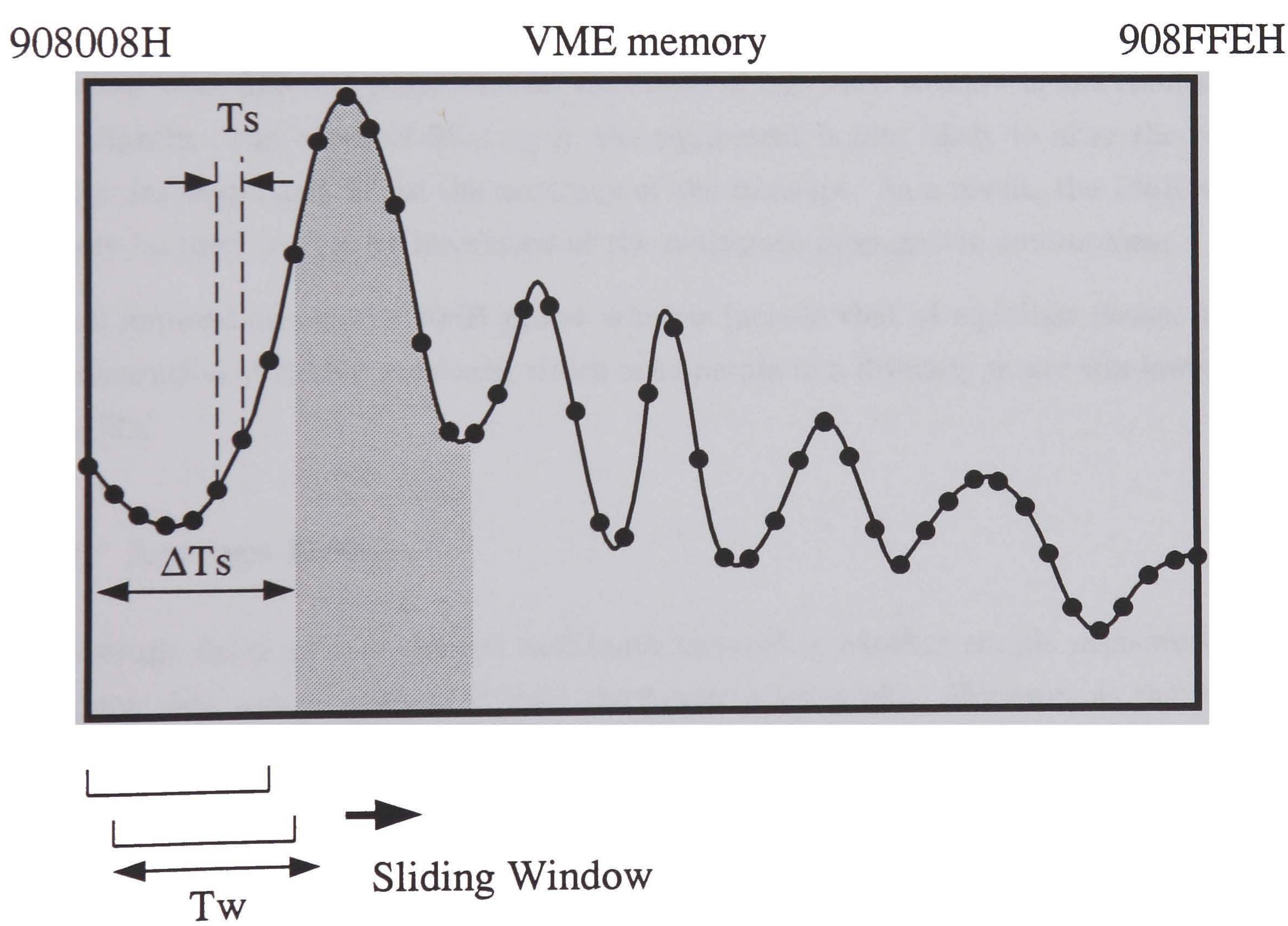

Figure 4.12: Extraction of the channel impulse response using a sliding window

The energy within the window at a time offset of ΔT_s is calculated as:

$$[E]_{t=\Delta T_s} = \sum_{n=0}^{N_w} |h(n+\Delta)|^2 \tag{4.21}$$

where $h(n)$ is the sampled channel impulse response, $N_w = t_w/T_s$ is the number of CIR samples in the sliding window, and T_w and T_s are the length of the sliding window and the sampling period, respectively.

Armed with the portion of the CIR extracted as described above, the channel parameters such as the 10dB power window, average delay (t_{mean}) and the root mean square delay spread (t_{rms}), can be calculated. The values of these parameters are interactively displayed on screen and stored in a data file for further processing.

4.8.1 10dB Power Window

The 10dB power window is the simplest measure used to analyse multipath time dispersion. It can be calculated from the power delay profile as the time during which the signal level is greater than one tenth of the amplitude of the most significant peak. However, this measure does not take into account the sounding pulse shape or width, so that if soundings were performed with different pulse widths, the result of the 10dB window of the results would differ slightly. The effect of filtering in the equipment is also likely to alter the received signal pulse shape and hence the accuracy of the measure. As a result, the 10dB window can only be used to give an indication of the multipath propagation environment.

Typical applications of the 10dB power window include that of equaliser design and the implementation of RAKE receivers, which can operate in a diversity power window of 10dB or less [22].

4.8.2 Average Delay

The average delay of a wideband multipath channel is another simple measure of time dispersion that can be calculated from the power delay profile. However, as the measure uses low power sections of the power delay profile, any noise added by the measurement equipment will affect the result. In an attempt to limit the effect of equipment and other extraneous noise sources, a threshold value is set at the noise floor of the received CIR. Any data points in the CIR's below this value are excluded form the calculations. For valid data points, the average delay spread is calculated as follows:

$$t_{mean} = \frac{T_s \sum_{n=0}^{N_w} n|h(n)|^2}{\sum_{n=0}^{N_w} |h(n)|^2} \tag{4.22}$$

4.8.3 Root Mean Square Delay Spread

The RMS delay spread is the most commonly used measure in multipath channel characterisation. It can be used to compare the multipath effects at different frequencies and in different environments. It is mathematically equivalent to the standard deviation of the power delay profile and hence gives a measure of the time taken for 85% of the total power to be received. Again, as noted in Section 4.8.2, the noise floor value of each CIR is used as a minimum valid signal threshold to prevent system noise from affecting the results of this calculation. The RMS delay spread can be calculated from the valid power delay data points as follows:

$$t_{rms} = \sqrt{\frac{\sum_{n=0}^{N_w} (nT_s - \mu)^2 \left|h(n)\right|^2}{\sum_{n=0}^{N_w} \left|h(n)\right|^2}} \tag{4.23}$$

4.9 System Test And Validation

Having developed the FFT channel sounder system to a functional stage, it was necessary to verify its operational parameters before proceeding to the field trial stage and subsequent data analysis.

Figure 4.13 shows a block diagram of the test configuration used to validate the FFT Dual-Channel Sounder system and Figure 4.14 shows a photograph of the system during a back-to-back test. One of the base station transmitters was used to provide a single path signal, using one of the preferred pair PN codes. This signal was then split into independent paths using a Hewlett Packard multipath simulator unit[1]. The simulator unit can provide up to three additional paths to the first or dominant path. Each path can be individually attenuated and delayed[2].

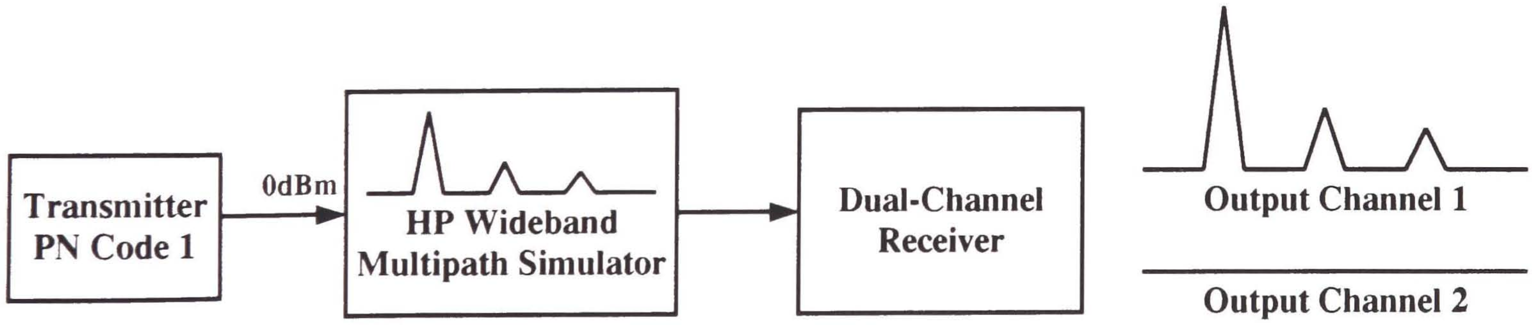

Figure 4.13: FFT Channel Sounder Calibration Block Diagram

[1] The maximum signal level of the transmitter output stage is limited to 0.0dBm peak power by the input signal constraints of the multipath simulator.

[2] Delays only up to a maximum time interval of 1 microsecond from the dominant path were possible using the multipath simulator unit.

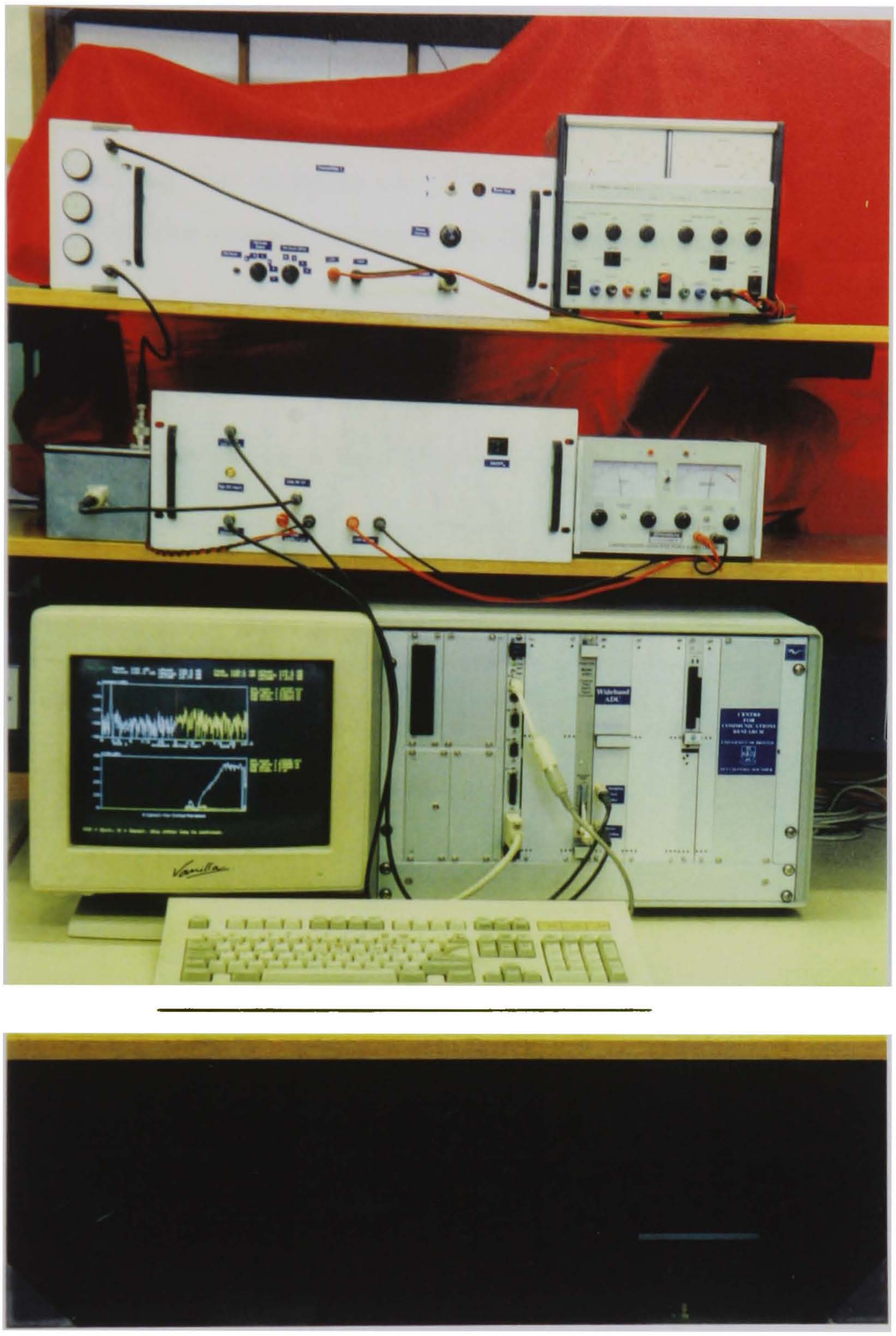

Figure 4.14: Photograph of Dual-Channel Sounder During a Back-to-Back Test

4.9.1 Delay Calibration

Figure 4.15 shows the power delay profile obtained from the FFT Dual-Channel Sounder with the Hewlett Packard multipath simulator unit. The unit was set to provide three similarly attenuated paths in addition to the dominant path. The three paths were delayed by 250ns, 500ns and $1\mu s$. The width of each sample shown in the delay profile is equivalent to the sample rate used by the sounder i.e. 4 samples/chip = 31.25ns. The power level shown is equal to each of the sample values from the resultant CIR, converted to decibels.

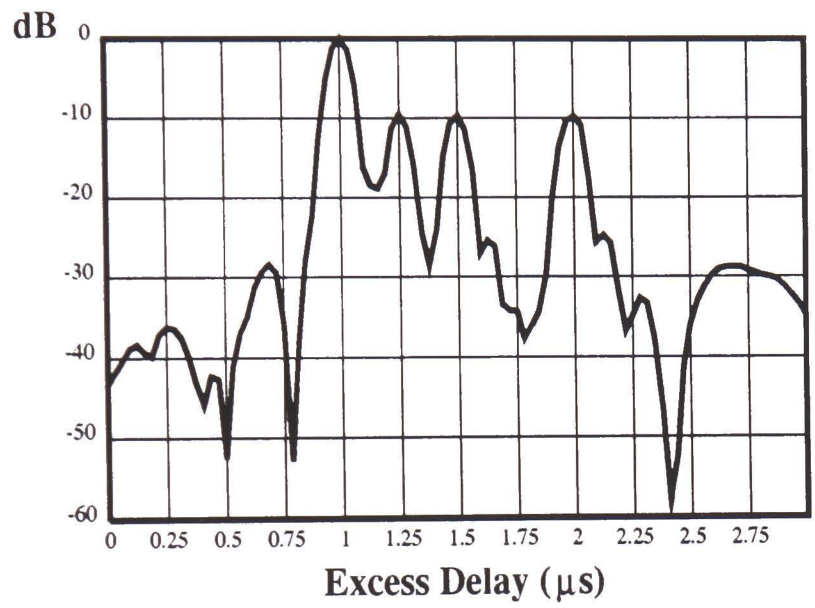

Figure 4.15: FFT Channel Sounder Delay Calibration CIR

4.9.2 Attenuation Calibration

The HP multipath simulator was used to provide two paths: a fixed dominant path and a second, variable level, delayed path, to be used for the attenuation calibration of the sounder. Figure 4.16 shows the results of the calibration test for the applied attenuation to the input against the observed attenuation of the FFT sounder CIR output.

4.9.3 Power Calibration

The FFT sounder system was calibrated for input power level at the receiver to the observed power level in the CIR output. The power level at the input to the receiver was measured using a Hewlett Packard 437B power meter. The results of input signal level vs. maximum observed value of the CIR (converted to dB) are plotted in Figure 4.17. A line was drawn at the observed signal level for the receiver input terminated with a 50 Ohm load. The regions near the start and end of the plot exhibit the linear operation boundaries of the FFT sounder. Signal levels into the ADC at these points are too large (causing overflow) or too small (in comparison to the noise-floor of the system) for the device to operate effectively.

Therefore, the approximate linear range of the FFT sounder is between an input signal level of -30dBm to -100dBm. The linear regression line shown in the plot has the equation:

$$\text{Input Power (dBM)} = 1.07 \times \text{Power Obs. (dB)} - 214.88 \tag{4.24}$$

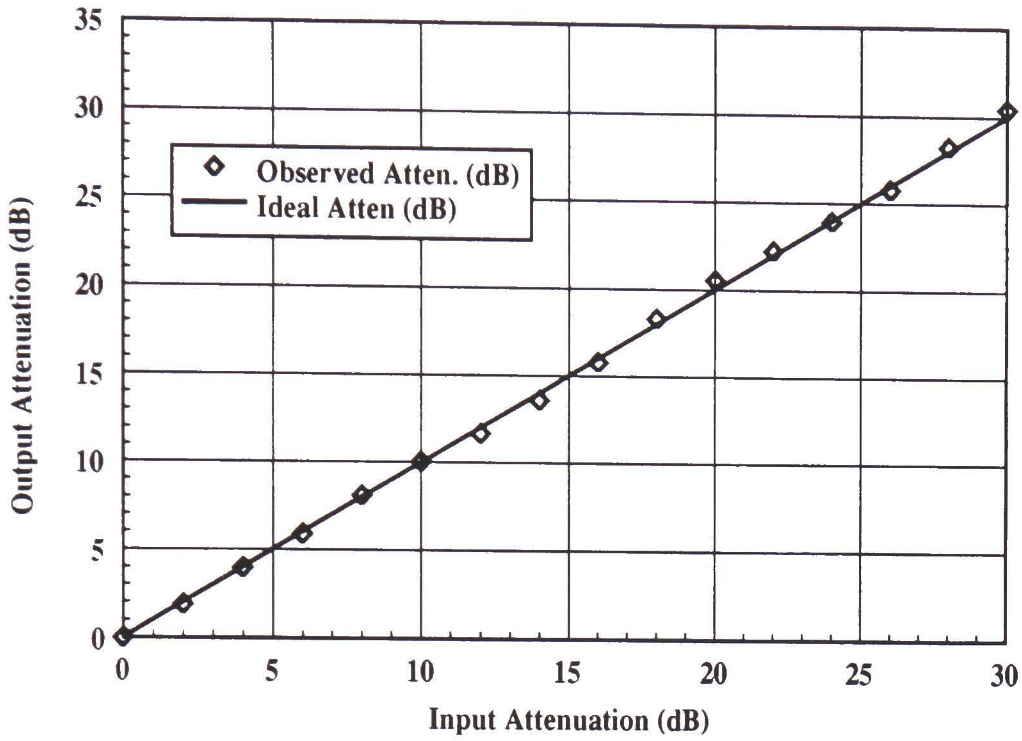

Figure 4.16: FFT Channel Sounder Attenuation Calibration

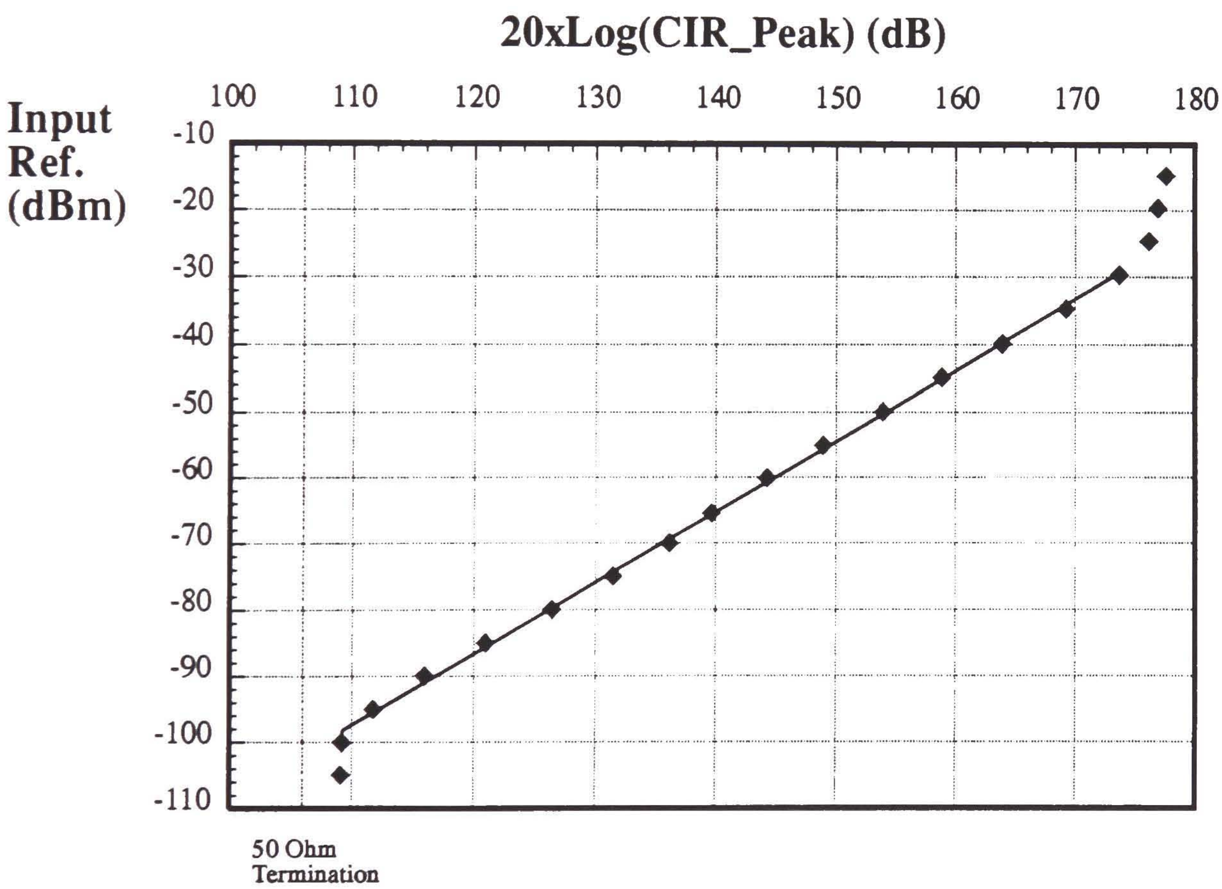

Figure 4.17: FFT Channel Sounder Power Calibration Curve

4.10 The Generic Handover Algorithm

In order that the data gathered from the field trials could be analysed to investigate the effects of the handover parameters on the downlink QoS, the generic handover algorithm (GHA) was written and developed.

The GHA was written to allow analysis for both hard and soft handover, using the same analysis procedure or software code. Hence, comparisons of downlink performance could be drawn directly between the two handover techniques, for a variety of system parameters, using the same set of field trial data. The main handover analysis procedure was written as a single, finite state machine in Borland C++.

The procedure adopts a system of sets and a reference signal level from the base stations, to control the handover process. The sets are: *ACTIVE SET*, *NEIGHBOUR SET*, *ADD SET* and *DROP SET*. Analysis of the resulting system performance is related to QoS by a set of system requirements discussed in Section 5.2, from which the handover parameters were then optimised.

4.10.1 Handover Sets

The *ACTIVE SET* contains a list of the base station(s) currently considered to be the most appropriate station(s) to be in control of a mobile call. This set is used to control the handover process selection. In the case of hard handover, this set can contain a maximum of one base station in its list of members. No further base station may be added to the list until the current base station has been removed from the list i.e. it has a maximum membership of one. Soft handover allows membership of more than one base station in this set.

The *NEIGHBOUR SET* contains a list of all available base stations not currently connected to the mobile i.e. the opposite of the *ACTIVE SET*. For the purposes of the field trial this set is only likely to contain a maximum of one base station.

The *ADD SET* is used to indicate when a base station, currently on the *NEIGHBOUR SET* list at a particular field trial measurement position, is under consideration for addition to the *ACTIVE SET*. The requirements for membership of this list are: the reference signal level of a base station must fall within a specified window, bounded by the maximum received signal strength from all base stations at that measurement position and a threshold value, Δ_{Thresh} dB, set below this value (See Section 4.10.3). Removal of a base station from this list can occur in one of two ways:

- Successful Removal. This occurs if the reference signal level of the base station under consideration remains a member of the set for a consecutive number of measurements such that a timer, t_{add}, expires (See Section 4.10.2). At this point the base station can be added the *ACTIVE SET* if the set is not full.

- Unsuccessful Removal. This occurs if the reference signal falls outside of the window. The base station is removed from the list and the timer, t_{add}, zeroed.

If, however, the timer t_{add}, expires but the *ACTIVE SET* is full i.e. possible in the case of hard handover, then the base station will continue to remain a member of the list until it is removed by one of the above two processes.

The *DROP SET* is similar in function to the *ADD SET*, except that the base station name is removed from the *ACTIVE SET* list when its reference signal falls outside of the window. Again this window is set relative to the maximum received reference signal level from all base stations at that measurement position, by the threshold value, Δ_{Thresh} dB. Removal from the set can also occur in one of two ways.

- Successful Removal. This occurs if the reference signal of the base station under consideration remains a member of the set for a consecutive number of measurements such that a timer, t_{drop}, expires (See Section 4.10.2). At this point the base station will be removed from the *ACTIVE SET* and placed in the *NEIGHBOUR SET*.
- Unsuccessful Removal. This occurs if the reference signal falls outside of the window. The base station is removed from the list and the timer, t_{drop}, zeroed, i.e. the base station remains a valid member of the *ACTIVE SET*.

4.10.2 Handover Timers

The timers t_{add} and t_{drop} are used in the handover algorithm to prevent premature handover. Their purpose is to allow the algorithm to assess whether a reference signal variation is likely to become a permanent improvement or degradation in the received signal level, by delaying the handover process for a number of samples.

In the case of hard handover, the timers are not required and so are set accordingly:

$$t_{add} = t_{drop} = 0.0s \tag{4.25}$$

In reality the timers become a function of mobile speed, due to the operation of the handover algorithm, e.g. if the mobile speed were assumed to be 10m/s and the separation between measurement analysis points of 0.5m, this gives a separation of 0.05s between sample points and hence the minimum timer increment.

A more practical measure could have been to use the actual speed of the test vehicle throughout the trial. Unfortunately, the speed of the test vehicle was limited by the data capture rate of the dual-channel FFT sounder, which would only allow a speed of up to 14mph (approximately 6m/s), taking one measurement every 0.5 metres. Also, mobile speeds may not be constant throughout measurements, due to environmental restrictions: turning corners, people crossing at junctions, etc. This would lead to an inaccurate interpretation of the environment and associated statistical changes with time. Therefore, throughout the handover algorithm analyses, the mobile speed was given an arbitrary value of 10m/s (and hence a timer minimum increment of 0.05s) both for simplicity and ease of interpretation of the results.

4.10.3 Reference Signal

The reference signal used in the GHA can be chosen from one of two types, both taken from the most significant received peak of the power delay profile from each channel by the dual-channel FFT sounder system. Due to the nature of the field trials, the received signals were taken as a pilot signal from each base station. The reference signal can be taken as either being the absolute received signal value in dBm, or can be calculated from the Signal-to-Interference-Noise Ratio (SINR) in dB. The second reference value allows for the cross-correlation interference level experienced by the presence of the alternative base station (Section 4.5.1) and hence gives a clearer indication of when a significant signal is present.

4.10.4 GHA Functionality Verification

Demonstration of the functionality of the GHA has been achieved by use of a test file containing a simulated received pilot signal from two base stations, in the same format as would be obtained from the dual-channel FFT channel sounder. The simulated received pilot signals are shown in Figure 4.18. In both soft handover and hard handover selection in the algorithm, a threshold level of 6dB was arbitrarily chosen and the mobile speed assumed to be 10m/s for ease of demonstration of the algorithm functionality. In the case of soft handover alone, the timers were set to $t_{add} = 0.1s$ and $t_{drop} = 0.2s$.

The results obtained from the algorithm are shown in Figures 4.19 to 4.22 and Table 4.1.

From Figures 4.19 and 4.20, it is clearly seen how the soft handover technique maintains the received SINR level above that obtained from the technique of hard handover, under the same signal conditions. With reference to Section 3.2, if the signal level in a real system were to drop below a minimum required SINR value, then there could be a severe degradation in the QoS provided by that communications link, which could even result in a call being

Handover Technique Used	Number of Handovers	1st H/O Start (m)	Soft H/O Region (m)	Total H/O Distance (m)	$SINR_{min}$ (dB)
Hard	2	17.0	-	20.0	6.0
Soft	2	13.5	9.0	24.5	11.0

Table 4.1: Generic Handover Algorithm Test Results

dropped. Hence, under the same conditions, soft handover is shown to be more likely to give a robust link.

It is also worth noting the two soft handover regions shown in Figure 4.22. Over these regions, the received signal strengths have been combined using maximal ratio combining (MRC) (Section 4.3.3), resulting in a signal strength enhancement, visible as the curved portions of Figure 4.20.

Evidence of the operation of the handover timers is shown for soft handover in Figure 4.22, with the appropriate presences of the base stations in the *ADD* and *DROP* sets. Using hard handover (Figure 4.21), the *ADD* set demonstrates how the *non-active* base station remains a member of the *NEIGHBOUR* set until the current *active* base station is *dropped*, when the reference signal level fell outside the 6dB threshold limit.

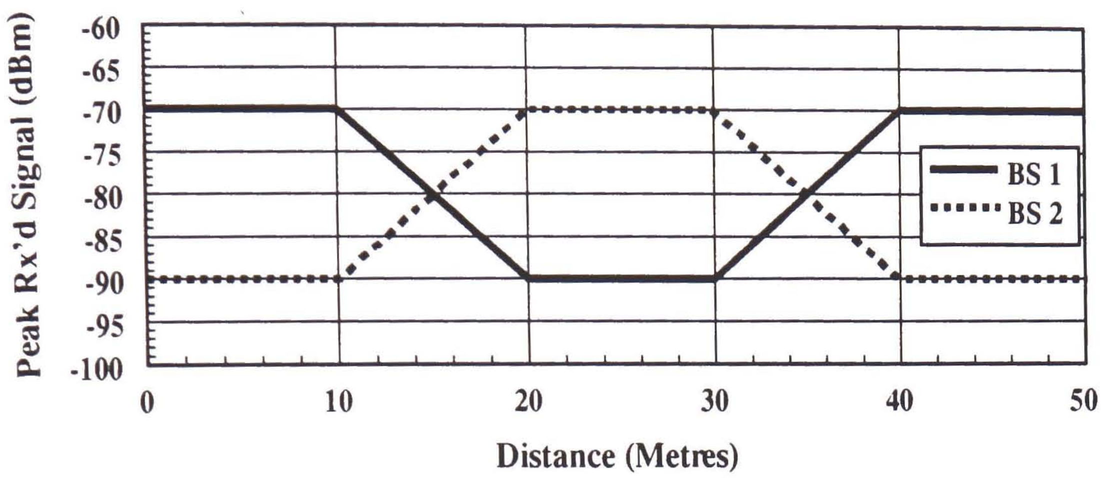

Figure 4.18: Test Received Pilot Signals

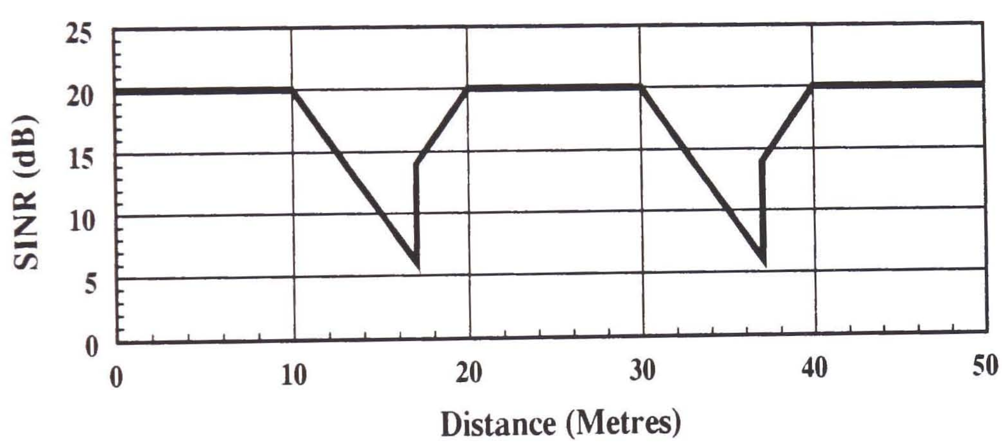

Figure 4.19: Hard Handover Resultant Signal

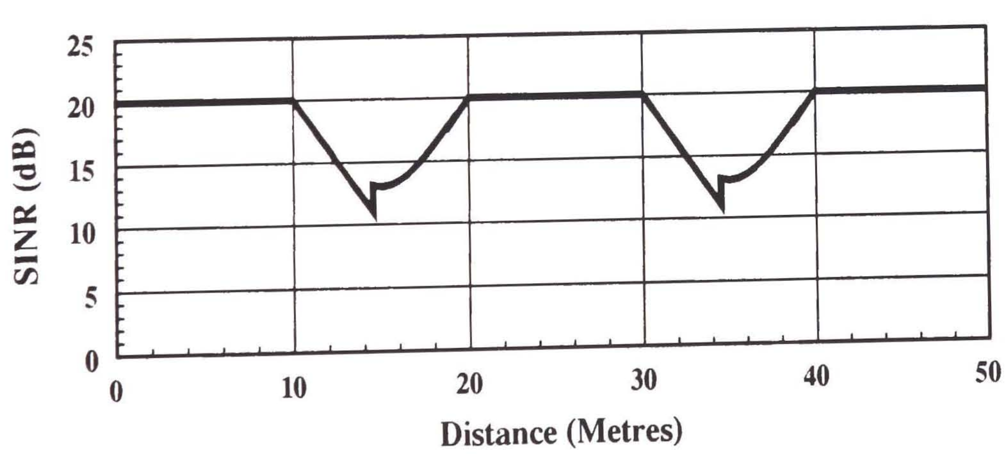

Figure 4.20: Soft Handover Resultant Signal

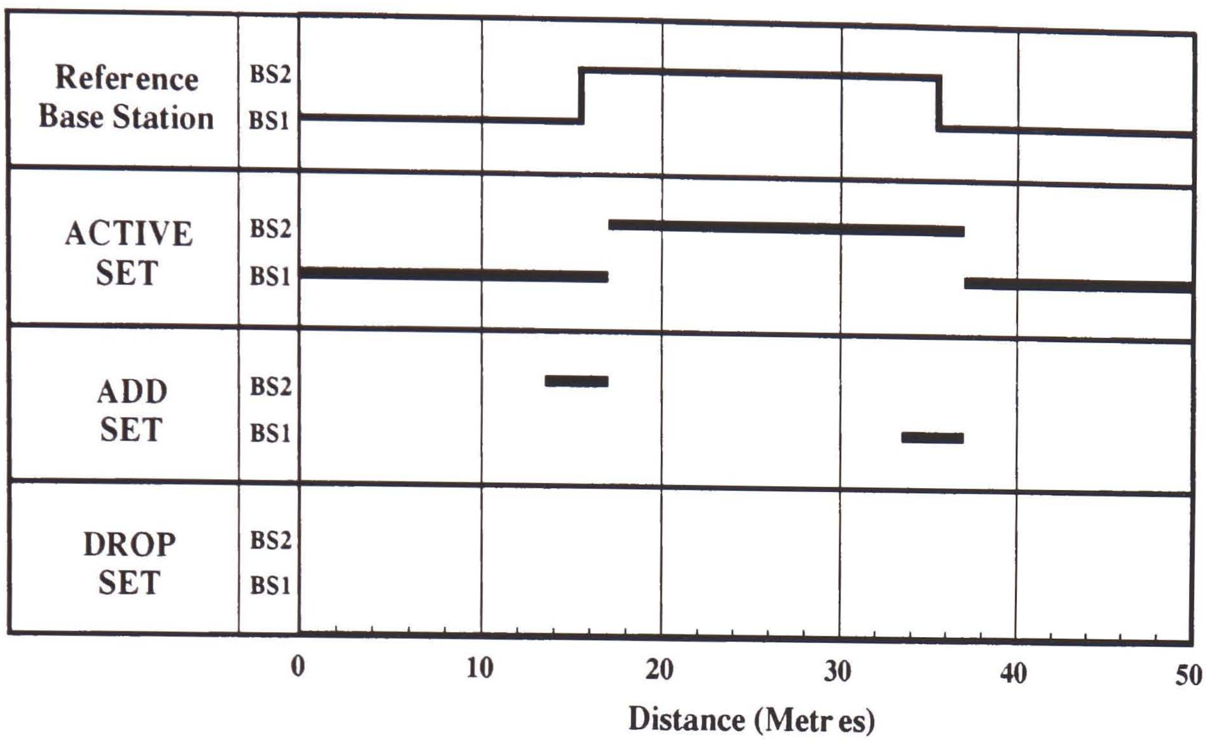

Figure 4.21: Hard Handover Sets

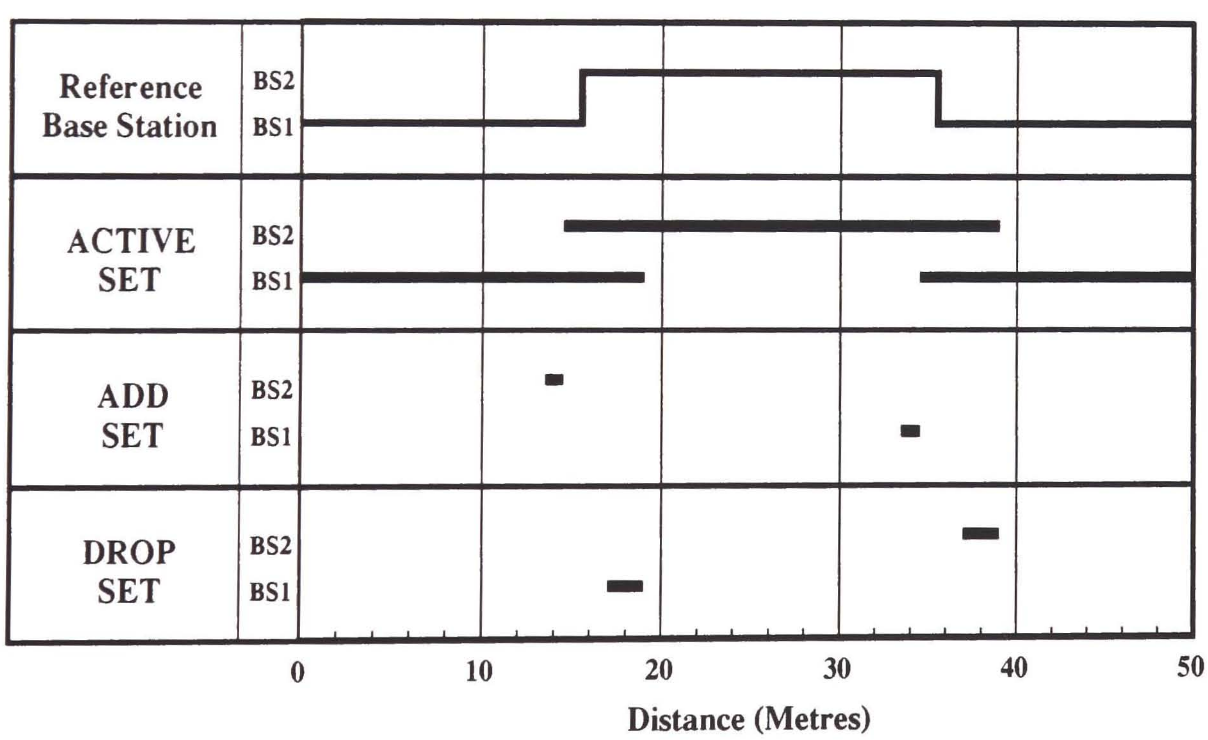

Figure 4.22: Soft Handover Sets

4.11 Equipment Used in Field Trial Data Collection

The following items of equipment were required for all the field trials performed:

- FFT Dual-Channel Sounder Receiver with Monitor incorporating a Wessex Low Noise Amplifier and BSC Bandpass Cavity Filter.
- Two 1.823GHz Transmitter Systems incorporating: Wessex ANP-0123S/0118S Power Amplifiers and Four BSC Bandpass Cavity Filters.
- Volvo 740 Estate with dual-battery and charging systems.
- 3 Jaybeam 2.2dBi Omni-directional Antennas.
- Bird Model 43 Watt meter.
- Clarke Tripod Model 5427.
- Clarke Pump-Up Mast Model 8285.
- Thurley Engineering Mast.
- EMS Power Systems 12v D.C./240v AC. 500watt invertor.
- Dryfit A200 12volt 110amp Acid Battery
- Two 240v AC. Petrol Driven Generators

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Chapter 5

Results of Propagation Measurements and Handover Analysis

"The success of UMTS relies not only on the development of a flexible air interface, efficient coding techniques, and handset technology; it is equally important to design a system that can support the underlying technology and to interface with other networks. Therefore, the proper design of the network, in order to provide sufficient capacity of high-quality coverage and efficient terminal mobility management, is of utmost importance."
- J. Cheung et al, IEEE Communications Magazine, *"Network Planning for Third-Generation Mobile Radio Systems"* [1].

5.1 Introduction

This chapter presents the results of the wideband channel sounding field trials taken in a variety of cellular handover scenarios. All field trial measurements were taken using the dual-channel FFT sounder described in Section 4.6, operating at a carrier frequency of 1823MHz. The data gathered from these soundings was analysed using the Generic Handover Algorithm described in Section 4.10, which enables the analysis of both hard and soft handover (Section 2.4). The parameters used in the handover algorithm were then optimised using a procedure described in Section 5.2, to achieve the best Quality-of-Service (QoS) communications link for the environment studied.

Trade-offs in the parameters versus QoS achievable were also examined to demonstrate the versatility of the handover analysis routine and benefits to the system implementation of the handover technique selected.

The experiments performed and analysis made of the results were not intended to produce a definitive solution to the problem of cellular handover, but to develop an analysis technique which can be followed to establish the relative merits or trade-offs possible, under any particular handover scheme. The technique can also be used to determine the sensitivity of the handover scheme to changes in its parameters.

For each scenario presented, a detailed description is given for the environment topology and measurements undertaken using the FFT channel sounder. Results will be given for the average propagation statistics obtained for each channel, with examples of the complex impulse responses (CIR's) obtained from a point along the study route. The data shown in these CIR's being normalised to the value of the most significant signal level received at the measurement location.

Presentation is then made of the results of the handover algorithm for each of the two reference signal types used: absolute signal value and SINR (Section 4.10.3). In each case, the received reference signal measurements obtained from the field trials is presented, along with the optimised results of the hard handover and soft handover study results.

The scenarios studied included three separate studies of microcellular-to-microcellular handover environments (Section 5.5) and three studies made of a macrocellular-to-microcellular handover environment (Section 5.6), each typical of the cell-types envisaged for UMTS (Section 2.2.2).

5.2 Handover Parameter Optimisation

The handover parameter optimisation was performed using the Generic Handover Algorithm (GHA) (Section 4.10) as the basis of the analysis procedure. The aim of the analysis was to produce a set of handover parameters which could be used to achieve a minimum Quality of Service (QoS) with consideration to the received signal strength and implications to the network operation. To achieve this aim, a set of system performance requirements were established which could be assessed using the GHA, using similar parameters to those in the earlier simulation study (Section 3.3). The basic system requirements, in order of importance, were as follows:

1. **Single Handover**. The parameters necessary to obtain a single handover were to be determined (where possible) within the specified handover threshold range. The range being 0dB to 8dB, in 1dB steps.

2. **Signal-to-Interference-Noise-Ratio**. A minimum value was set for the Signal-to-Noise-Interference Ratio, $SINR_{Req}$, below which the signal level should not fall at any point in the resultant received signal strength at the mobile, determined by the GHA. Ideally, for the noise-limited system of DS-CDMA, the larger the SINR minimum value that can maintained, the more reliable and robust the communications link will become to interference from other sources e.g. other mobile users in the same cell area. The minimum value was taken as $SINR_{Req} = 5$dB, which complies with the value used for the simulation study and with that given by Qualcomm Inc. [2] as the minimum level for the forward or downlink to maintain a satisfactory communications link.

3. **Capacity**. Using the simulation data (Section 3.3) it was found that the capacity of a cellular system could be influenced by the handover threshold required. The capacity of a hard handover system was found to fall as the threshold was increased, hence the minimum handover threshold to satisfy the system's operational requirements would maximise cell capacity. In contrast, a threshold value of between 4dB and 6dB was found to maximise the cellular capacity for a system employing soft handover[1].

4. **Network Loading**. This consideration is more applicable to the case of soft handover than hard handover, where more than one base station can be transmitting the same information to a single mobile. This is also true of the reverse link, where signalling traffic will be doubled all the way back to the MSC [3]. Although this signalling can be used to enhance the communications link, it does create a level of redundancy

[1]However, the influence which the soft handover timers would have on this capacity could not be gauged, due to the static nature of the mobile placements within the simulation study

within the network. Without this consideration, the optimisation of any soft handover situation would be to combine all available signals to achieve the optimum received signal strength i.e. mobiles would remain almost permanently in a state of handover.

5.2.1 Hard Handover Analysis

In the case of hard handover (Section 2.4.1), a simple handover threshold was used on the field trial data collected. Timer constraints on the algorithm were not imposed i.e. the condition $t_{Add} = t_{Drop} = 0.0$ was used throughout the analysis. The following service measures were calculated for each threshold value applied:

- Resultant number of handovers for threshold window applied.
- Total distance from first handover to final handover in the study.
- Location of first handover on study route.
- The minimum value of the resultant Signal-to-Interference-Noise Ratio $SINR_{min}$ experienced by the mobile station, according to the GHA.

The optimisation of the hard handover process is then a simple selection process from the resultant data. The selection being: for each reference signal type, establish the minimum handover threshold to satisfy most of the system requirements.

5.2.2 Soft Handover Analysis

In the case of soft handover (Section 2.4.2), the field trial data was analysed to establish parameters which would permit only a single handover, for the following three cases:

- **Case 1 : Maximise Received Signal Strength for Minimum Timer Values.** The GHA was used to find the minimum value of the timers t_{Drop} and t_{Add} to maximise the minimum value of the Signal-to-Interference-Noise Ratio, $SINR_{min}$[2] at the specified handover threshold for the environment selected. Intuitively, the minimum value of the add timer is zero. Hence, this method establishes the minimum size of the soft handover region for a single handover, using the drop timer and threshold value alone.

[2]Note: If the mobile receiver is considered to be undergoing soft handover, then the signals at the receiver were combined using a MRC technique (Section 4.3.3).

- **Case 2 : Minimise Drop Timer to Reduce Soft Handover Region.**

  The GHA was used to find the minimum value of the drop timer $t_{Drop}min$, using the add timer, t_{Add}, at each specified handover threshold for the environment selected. This effectively reduces the soft handover region from that given by Case 1, where possible.

- **Case 3 : Maximise Add Timer To Reduce Drop Timer but Maintain Minimum Required SINR.**

  The GHA was used to find the maximum value of the add timer, $t_{Add}max$ to achieve a $SINR_{min}$ of at least $SINR_{Req}$. The minimum drop timer value for this value of t_{Add} is noted to reduce the resultant soft handover region. Increasing the value of the drop timer beyond this value will increase the soft handover region size, but not compromise any other statistics.

These three cases are used to demonstrate the trade-offs possible in the soft handover scheme, as well as to allow flexibility in the optimisation process. For example: If a network operator regards the minimum received signal level as the most important aspect of the planning process, he could accept the result of optimising the parameters to Case 1. However, the parameters to achieve this may result in a large soft handover region and therefore potentially increase the signalling load to an unacceptable level to make the cell's operation viable. Hence the need to demonstrate the trade-offs possible in the specification of such parameters.

Optimisation of the soft handover process then becomes: to establish which of the three cases can be applied to satisfy most of the system requirements.

5.3 Algorithm Parameters

For the analysis of each of the study environments, certain parameters remained fixed. These are shown in Table 5.1. The mobile speed, and hence timer increment, were chosen for ease of interpretation of the results (Section 4.10.2). The threshold values were taken over the same range as the simulation study (Section 3.3), the interval between measurements was defined by the FFT channel sounder measurement technique and the value of $SINR_{Req}$ taken from the Qualcomm Inc. minimum value for reliable operation of a DS-CDMA downlink [2].

Mobile Speed	Timer Increment	Threshold Range	Threshold Increment	Snapshot Interval	$SINR_{req}$
10.0 m/s	0.05 s	0.0→8.0dB	1.0dB	0.5m	5.0dB

Table 5.1: Generic Handover Algorithm Fixed Parameters

5.4 Channel Characteristics

The channel characteristics were calculated from the received instantaneous CIR's for each base station according to the equations in Section 4.8. The values given are the average of all valid calculations, for each channel in the particular handover scenario.

Other propagation characteristics commonly quoted to define the environment, such as the path loss and fading components, prove harder to calculate accurately, due to the measurement process i.e. exact distance from base stations is unknown and measurements are spaced at intervals of 0.5 metres $\gg \lambda/2_{1.823GHz} = 8.2$cm.

5.5 Microcell-to-Microcell Handover Scenarios

Three microcell-to-microcell handover scenarios were studied, to examine the effect of different propagation environments, common to the proposed UMTS microcellular structures (Section 2.2.2), on the handover schemes.

The parameters used for the FFT dual-channel sounder set-up for the trials were as shown in Table 5.2, heights being measured relative to ground level and output power measured at the output of the transmitter unit. The antennas used on both the mobile test vehicle and transmitter masts were Jaybeam 2.2dBi omni-directional antennas. Further details of equipment used for field trials are given in Section 4.11

Test Vehicle Speed	Rx. Antenna Height	Tx. Antenna Height	Tx. Output Power
≈6m/s	1.5m	3.0m	24dBm

Table 5.2: Microcell-to-Microcell Scenario Parameters

5.5.1 Street-Corner Handover

Figure 5.1 shows a map indicating the location of the microcellular base station transmitter sites set up in Woodland Road and Priory Road, a suburban area close to the University of Bristol. On each side of the roads are low stone walls, approximately 1 to 2 metres in height, set back from which are rows of terraced, stone-fronted residential housing, now used as University Buildings. Analysis of measurements has been made over a forty metre section of the route, using the apex of the corner to approximately mark the middle of the run.

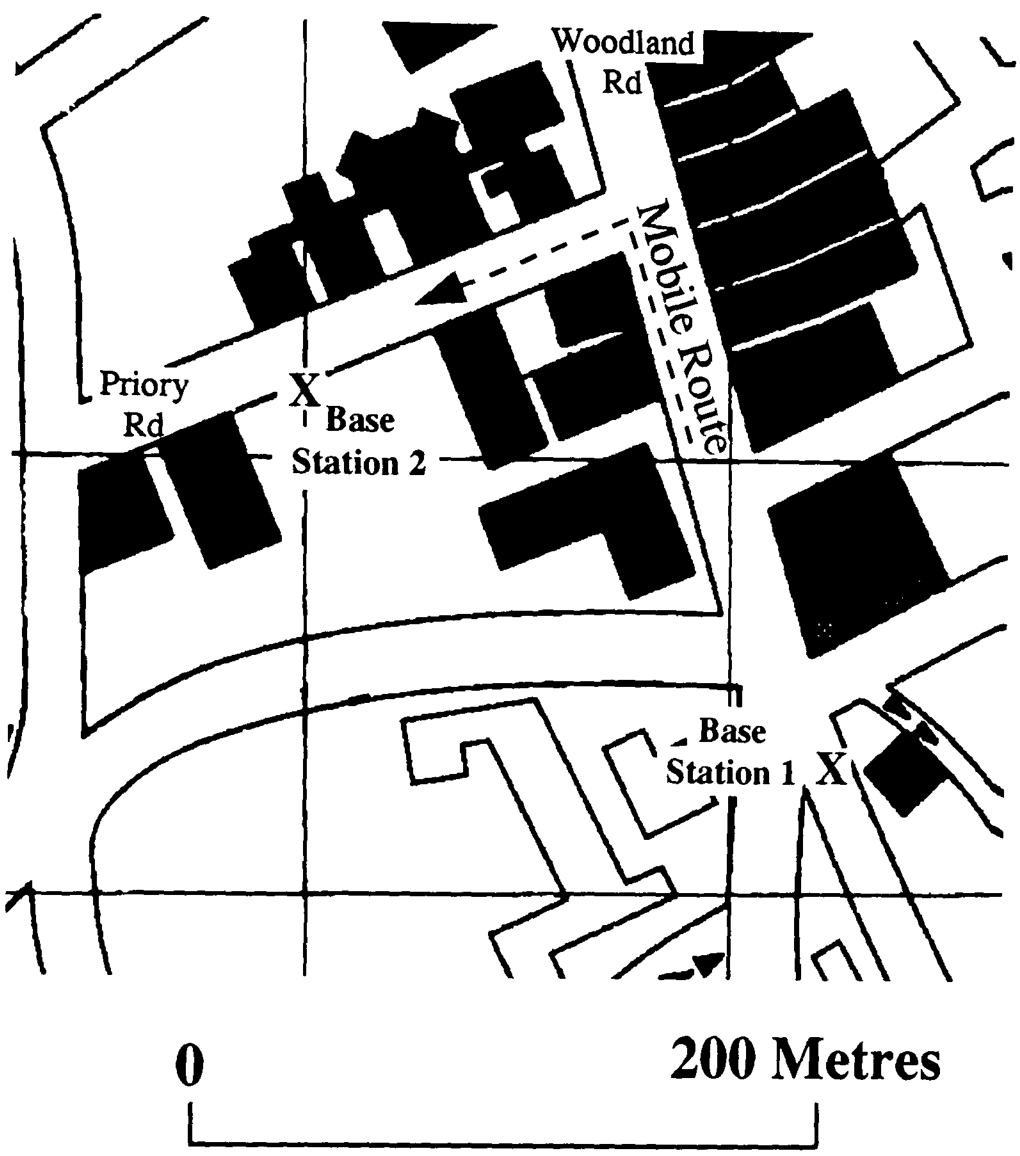

Figure 5.1: Map of Woodland Road and Priory Road,Bristol

Simultaneous CIR's from each base station were taken along the length of the route at intervals of 0.5m. An example of the CIR's obtained for each channel, taken at a measurement location close to the street corner and normalised to the peak received response, are shown in Figures 5.4 and 5.5. The average channel parameters calculated from all CIR's for the study (see Section 4.8) are presented in Table 5.5. The channel characteristics obtained are typical of a microcellular environment [4] and, as should be expected for this scenario, the characteristics of both channels are similar. There is evidence of a secondary multipath component in Figure 5.5, most likely a reflection of the second base station's signal from a nearby structure on Woodland Road. The RMS delay spread is the measure usually used to provide an insight into the data-rate capacity of the environment [5], although this is dependent on the modulation scheme adopted by the system.

The value obtained for the cross-correlation factor of the signals shows that there may be only a small relationship between the signal sources and their fading characteristics. Ideally, no relationship between the sources would permit the greatest benefit from signal combining, although the value is likely to be linked to the low signal shadowing present in the environment and rapid signal degradation. The negative value indicates the nature of the measurement run i.e. the mobile is moving away from one signal source and directly towards another.

Figures 5.6 and 5.7 show the reference signals used in the GHA analysis of the environment for the case of pilot signals and SINR respectively. The environment almost exhibits the classical handover shape (as depicted in Figure 2.3), with evidence of low fading in the received signal measurements prior to the sharp degradation of signal strength at approximately the mid-point of the run. This point coincides with the junction of Priory Road and Woodland Road and hence the test vehicle coming into a LOS position with the second transmitter. The fading was found to have a standard deviation of the order of 2dB, although this value cannot be attributed directly to either the shadowing or fast fading component, as explained in Section 5.4.

Rapid degradation of signal strength has been observed at street corners before, with typically 20 to 30dB changes within 10 to 20 metres [6] [7]. This demonstrates the excellent site shielding of the transmitters from each other and therefore the need for provision of separate microcellular coverage areas in this environment.

A major contributory factor to the rapid loss of nearly all signal strength from channel one, observable in the latter part of Figure 5.7, is likely to be due to signal *"masking"* by cross-correlation noise (Section 4.5.1) i.e. the proximity and strength of the second transmitter coming into LOS has created cross-correlation noise in the first channel at a higher level than the received signal strength. If the second transmitter were not present, then signals would still be observed from the first transmitter. This behaviour is confirmed by Figure 5.6, where the received signal strength of the second transmitter *'tracks'* the stronger signal of the second transmitter. In fact the received signal strength indicated from this point is cross-correlation noise.

The full results of the handover optimisation process are presented in Section B.1, Tables B.1 to B.4, where analysis has been performed for both reference signal types.

As examples of the operation of the GHA , Figures 5.8 and 5.9 show the computer screen results obtained using arbitrary values for the parameters in hard and soft handover respectively. The screen is split into two windows: the upper window showing the membership of the base stations to the sets used in the GHA analysis (Section 4.10.1), whilst the lower window shows the received signal strength from each base station (shown in yellow and green) and the resultant received signal strength at the receiver, according to the handover scheme (shown overlayed in red).

Reference Signal	Threshold Δ_{Thresh}	No. H/o's	$SINR_{min}$
Pilot	0.0dB	1	6.8dB
SINR	2.0dB	1	16.9dB

Table 5.3: Optimised Hard Handover Results: Street-Corner Handover

Reference Signal	Case	Threshold Δ_{Thresh}	Timer 1 t_{Drop}	Timer 2 t_{Add}	Soft H/o Region	$SINR_{min}$
Pilot	1	8.0dB	0.65s	0.00s	22.5m	19.8dB
	2	1.0dB	0.30s	0.00s	6.5m	19.0dB
	3	0.0dB	0.00s	0.00s	0.0m	6.8dB
SINR	1	0.0→3.0dB	0.25s	0.00s	5.5m	19.0dB
	2	0.0→8.0dB	0.05s	0.05s	0.0m	6.8dB
	3	0.0→3.0dB	0.05s	0.05s	0.0m	6.8dB

Table 5.4: Optimised Soft Handover Results: Street-Corner Handover

It is worth noting the anomalous situation in Table B.3, where the handover threshold of 1dB results in a situation where a value of $t_{Add} = t_{Drop}$ is not viable under the constraints of providing a single handover and maintaining a link minimum SINR $\geq$ 5.0dB due to the rapid signal degradation discussed earlier in this section.

Figure 5.2: Photograph of Woodland Road from BS1

Figure 5.3: Photograph of Priory Road Towards BS2

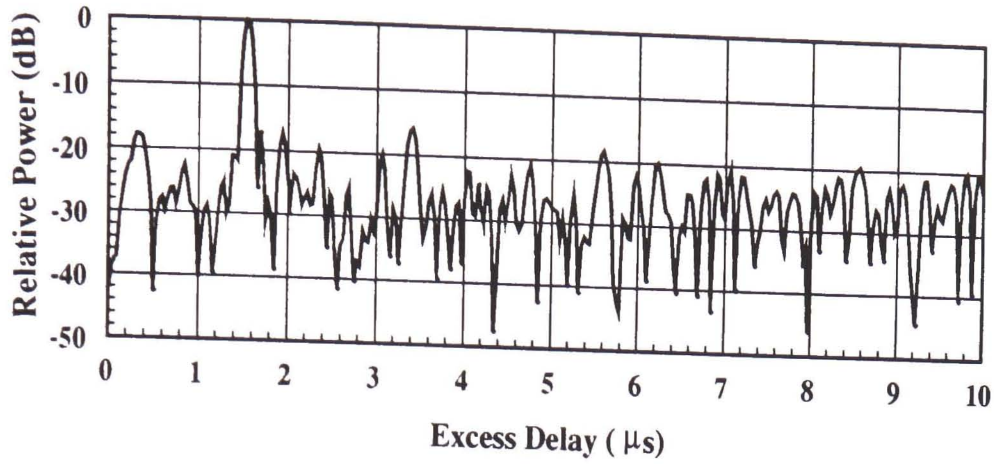

Figure 5.4: Typical CIR for Channel 1: Street-Corner Handover

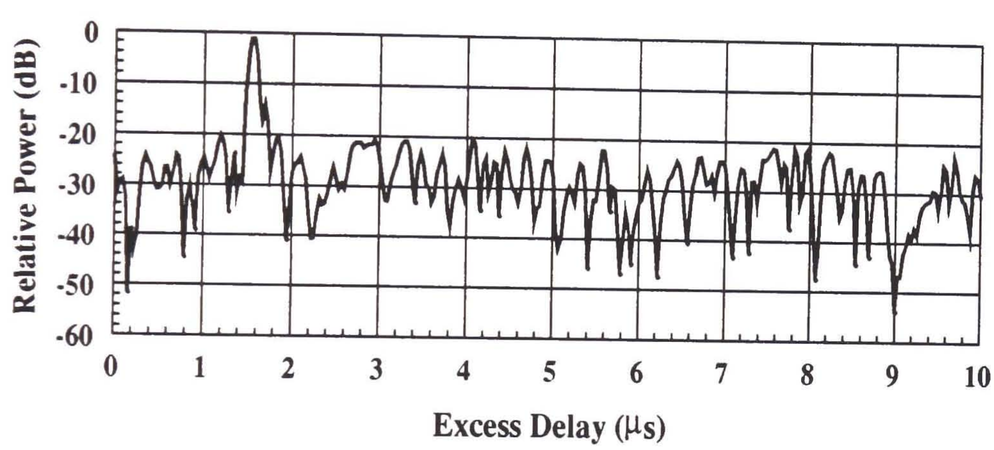

Figure 5.5: Typical CIR for Channel 2: Street-Corner Handover

Channel No.	Mean Delay Spread (ns)	RMS Delay Spread (ns)	10dB Window (ns)	Cross-Correlation
1	49.1	154.3	140.4	-0.727
2	49.3	132.1	178.9	

Table 5.5: Average Channel Characteristics : Street-Corner Handover

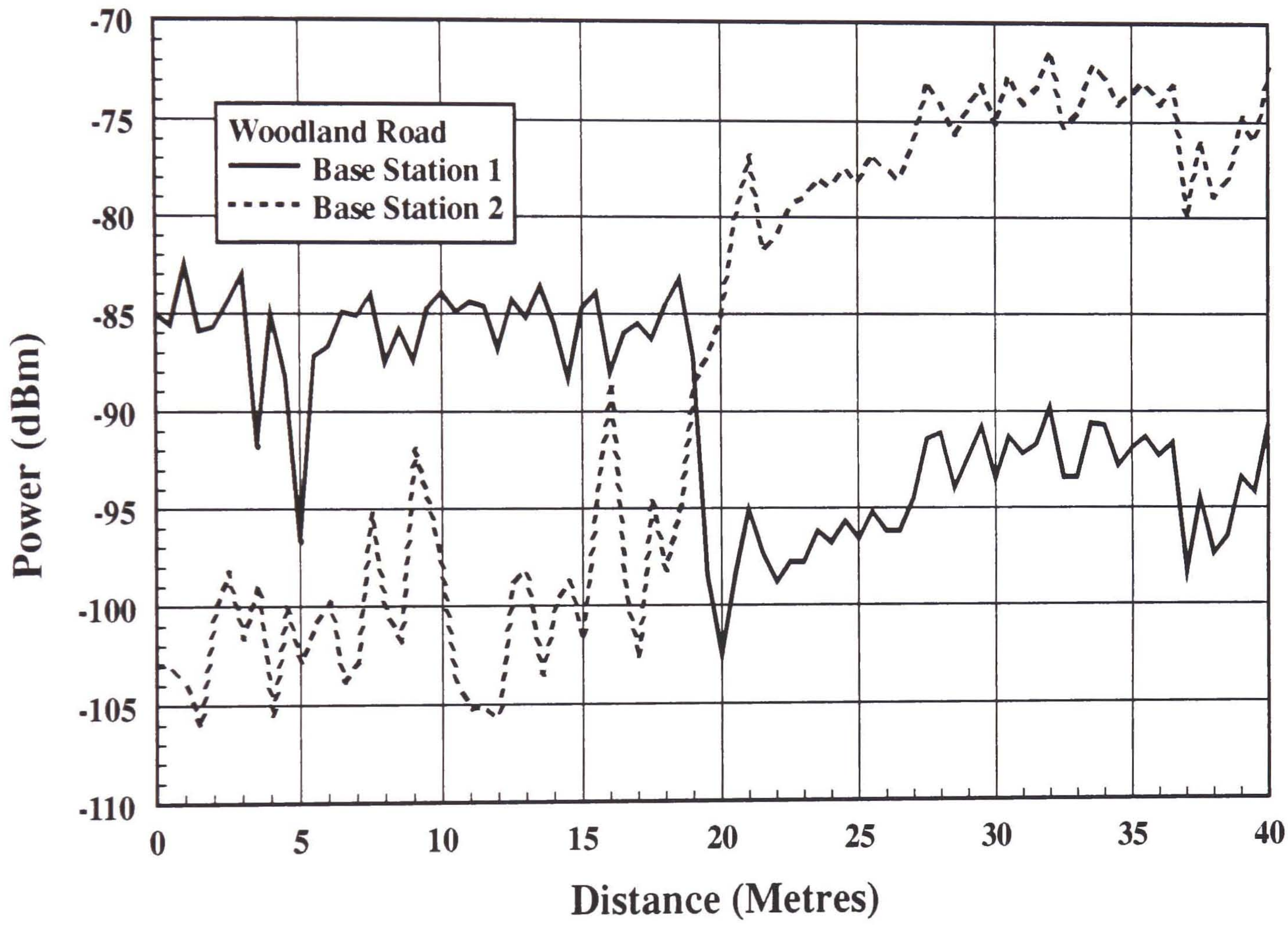

Figure 5.6: Received Pilot Signal vs. Distance: Street-Corner Handover

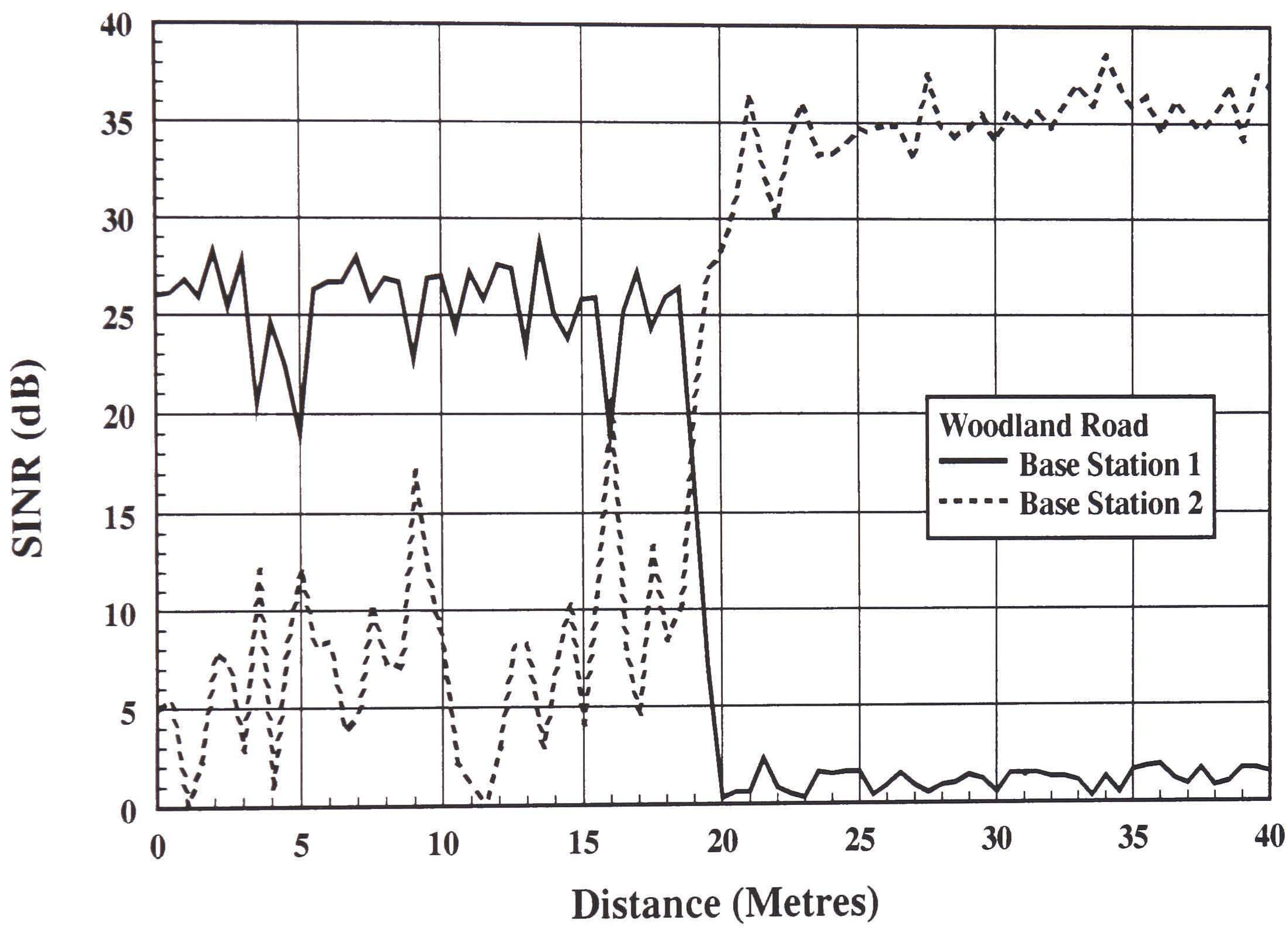

Figure 5.7: Signal-to-Interference-Noise Ratio vs. Distance: Street-Corner Handover

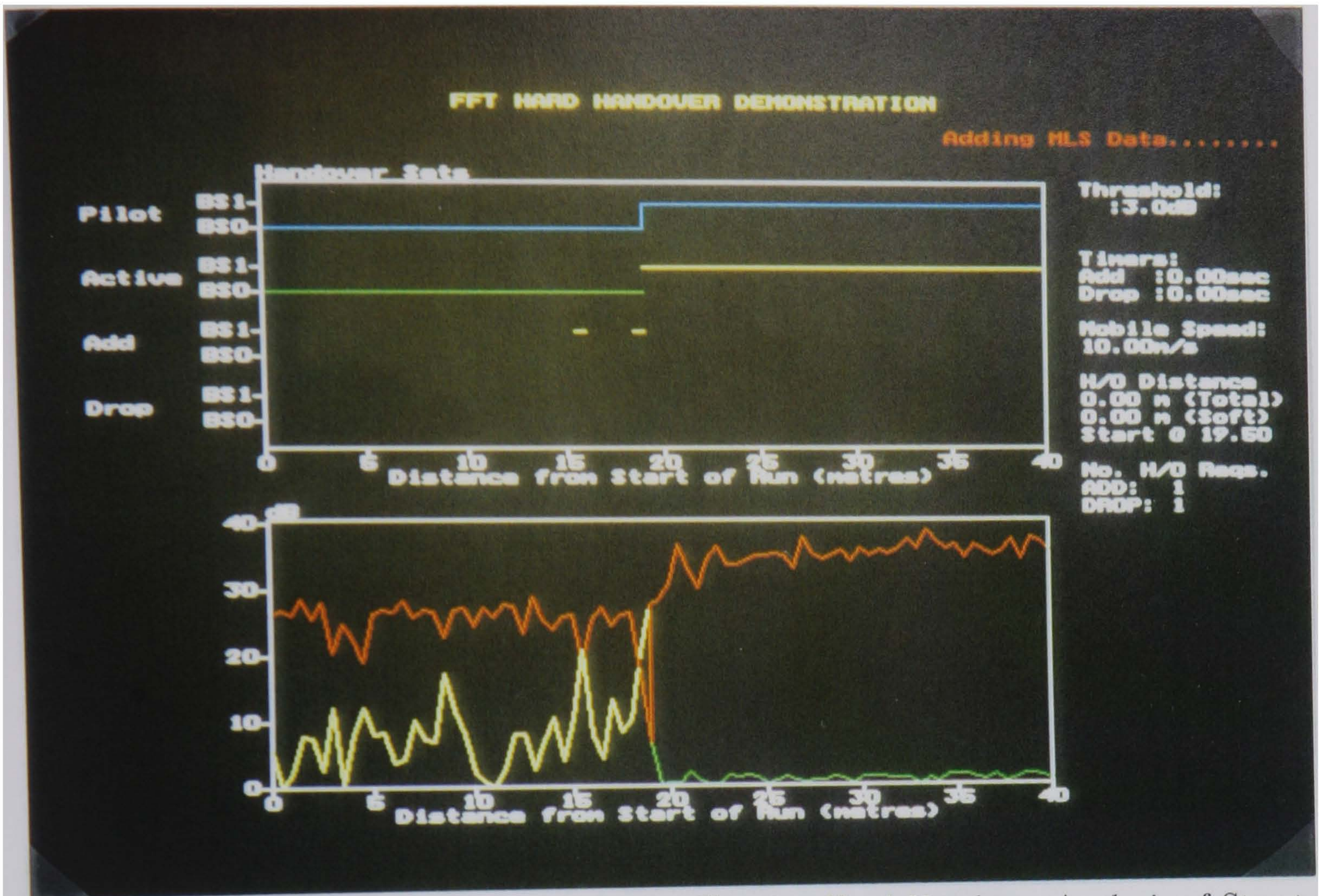

Figure 5.8: Photograph of Computer Screen Showing Hard Handover Analysis of Street Corner Scenario

Figure 5.9: Photograph of Computer Screen Showing Soft Handover Analysis of Street-Corner Scenario

5.5.2 Steep Hill Environment

Figure 5.10 shows a map indicating the locations of the two microcellular transmitters set up in Park Street, Bristol. This is a sloping street bordered on either side by rows of three storey shops and restaurants. These buildings are predominantly glass-fronted on the ground floor, with stone and glass fronts on subsequent floors. Measurements were taken from the top of Park Street and down towards the second transmitter located near the base of Park Street on College Green. Measurements have been analysed for a 250 metre section of the field trial data. Figures 5.12 and 5.13 show the reference signals used for the analysis of the route by the GHA.

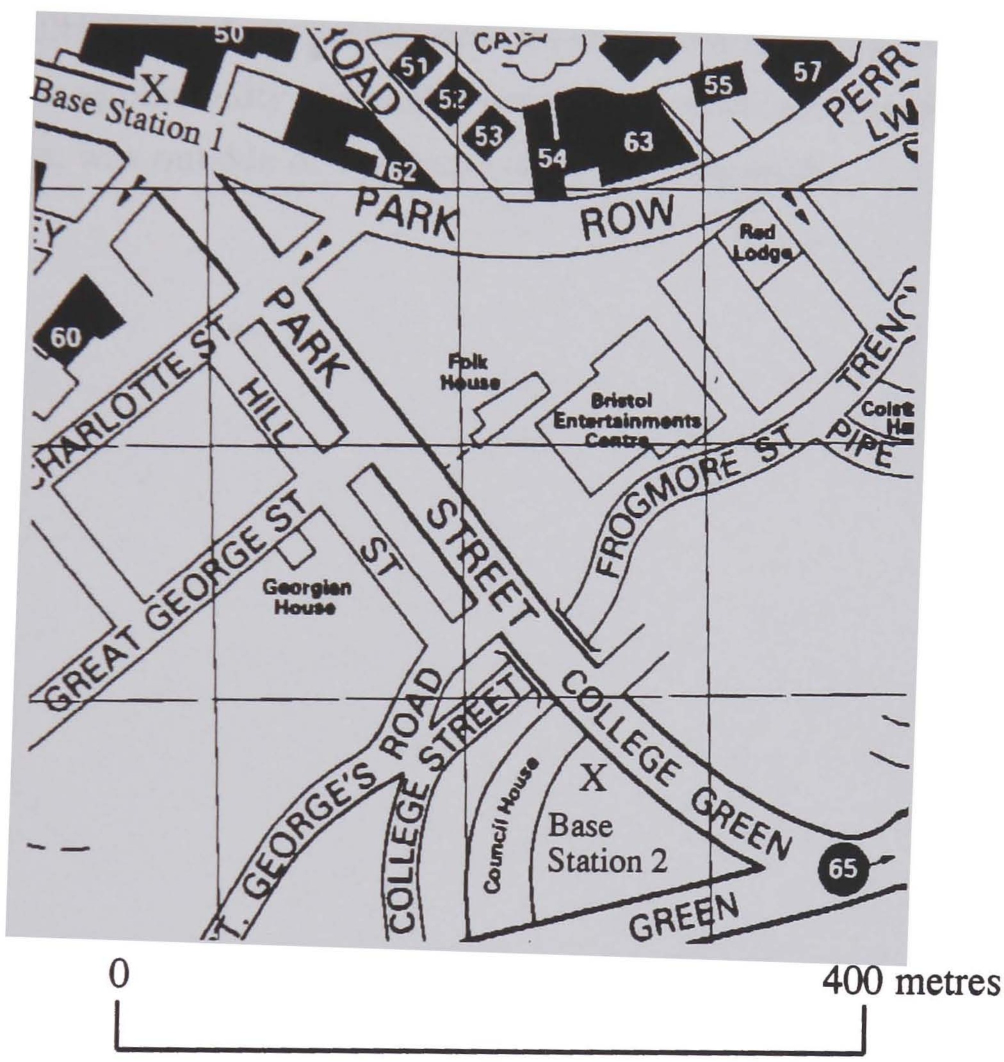

Figure 5.10: Map of Park Street, Bristol

The location of the transmitters on Park Street provides an interesting scenario. Figure 5.11 shows a photograph of Park Street, taken from the roof of a building, above the first base station (BS1), facing towards the second base station (BS2). Referring to both of these figures, the two microcellular base stations would appear to provide LOS coverage for the entire length of the study route. However, due to the shape of Park Street, LOS communications is lost shortly after the start of the run, after the vehicle proceeds down the hill. LOS with the first transmitter is regained to some extent towards the end of the run where the street levels out into College Green, hence the rise in received signal strength for base station 1 in Figure 5.13. However, preliminary analysis of the reference signals would indicate that a more viable handover region could exist prior to this re-establishment of a direct communications link, at around the 100 metre mark.

The average channel parameters are presented in Table 5.8. Again, the values obtained are typical for a microcellular environment and show little correlation between the signal sources. The RMS delays spreads are larger than for the previous study, as would be expected from the more open surroundings i.e. length of Park Street and tall *"reflective"* buildings and are of the order of 200ns. Signal fading is also higher, for similar reason and has a deviation from the received signal of around 3dB.

Analysis of the environment by the GHA is presented in Tables B.5 to B.8. It is clear from the results that the application of hard handover in this case would be unsuitable since it would require multiple handovers. this could be alleviated if a signal averaging process were used, although the applicability of signal averaging, at consecutive measurement points with a spacing of 0.5m, was outside of the scope of the investigation.

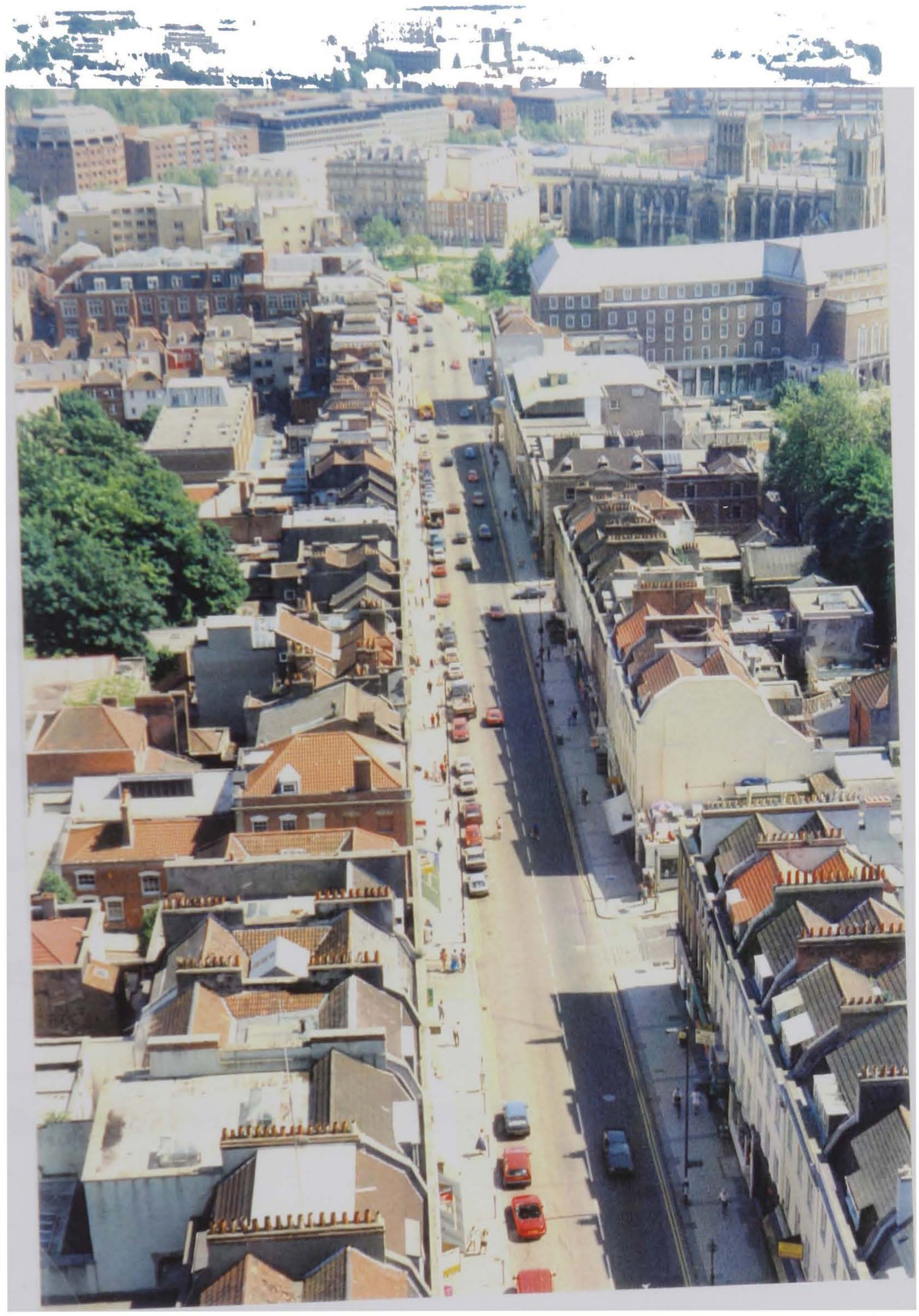

Figure 5.11: Photograph of Park Street From Above BS1, Facing Towards BS2

Reference Signal	Threshold Δ_{Thresh}	No. H/o's	$SINR_{min}$
Pilot	7.0dB	5	9.2dB
SINR	8.0dB	7	9.2dB

Table 5.6: Optimised Hard Handover Results: Steep Hill Environment

Reference Signal	Case	Threshold Δ_{Thresh}	Timer 1 t_{Drop}	Timer 2 t_{Add}	Soft H/o Region	$SINR_{min}$
Pilot	1	0.0→2.0dB	4.95s	0.00s	241.0m	17.7dB
	2	6.0dB	0.30s	0.25s	64.0m	16.0dB
	3	3.0→5.0dB	1.15s	1.15s	8.5m	10.0dB
SINR	1	6.0dB	3.05s	0.25s	217.0m	17.7dB
	2	7.0dB	0.35s	0.25s	61.5m	16.0dB
	3	6.0→7.0dB	1.15s	1.15s	8.5m	10.0dB

Table 5.7: Optimised Soft Handover Results: Steep Hill Environment

Channel No.	Mean Delay Spread (ns)	RMS Delay Spread (ns)	10dB Window (ns)	Cross-Correlation
1	49.8	213.0	228.6	-0.339
2	49.5	209.7	187.2	

Table 5.8: Average Channel Characteristics: Steep Hill Environment

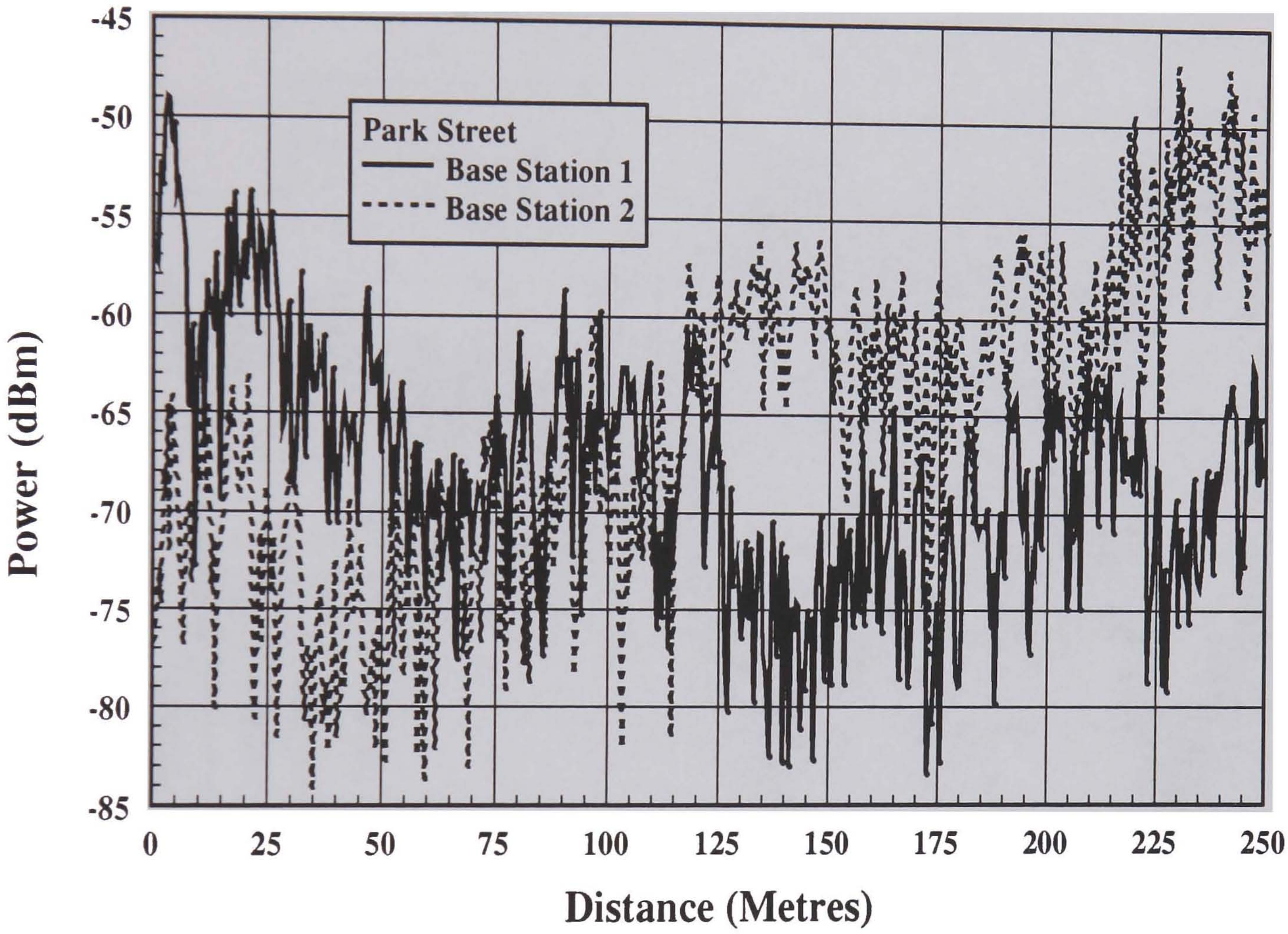

Figure 5.12: Received Pilot Signal vs. Distance for Park Street

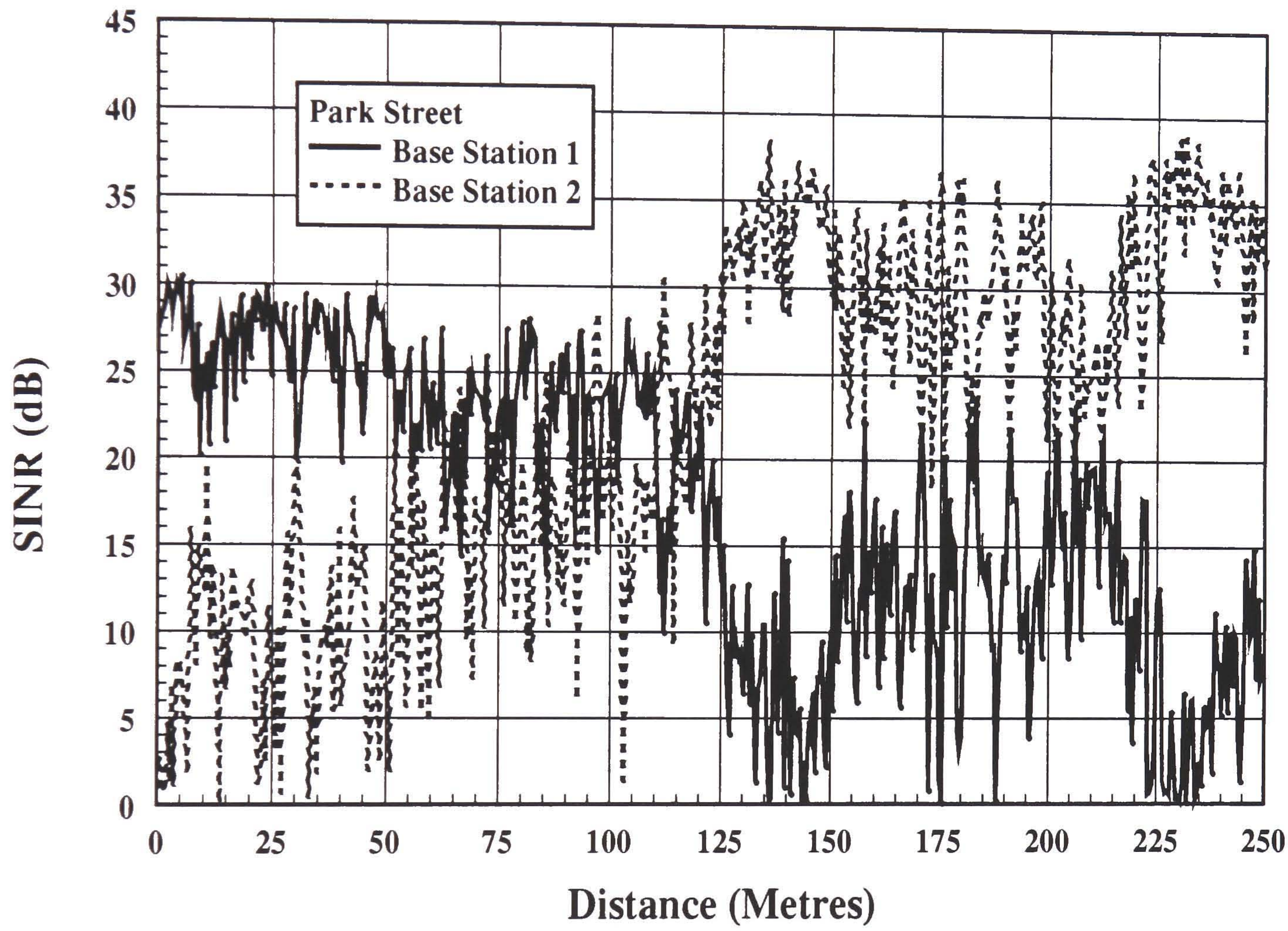

Figure 5.13: Signal-to-Interference-Noise Ratio vs. Distance: Steep Hill Environment

5.5.3 Street Canyon Environment

Figure 5.14 shows a map indicating the locations of the base station transmitters set up in University Walk, Bristol. This is a driveway located outside the Engineering Department at the University. Figure 5.15 shows a photograph taken from above the location of base station 1, facing along University Walk towards base station 2. It is flanked on one side by a stone wall (just over 3 metres high) and on the opposite side by University Buildings (shown in black) and car parks, resembling in some ways a *"street canyon"*. Measurements were taken over a seventy metre region, with the apex of the corner between the base stations marking the central position. These are presented in Figures 5.16 and 5.17.

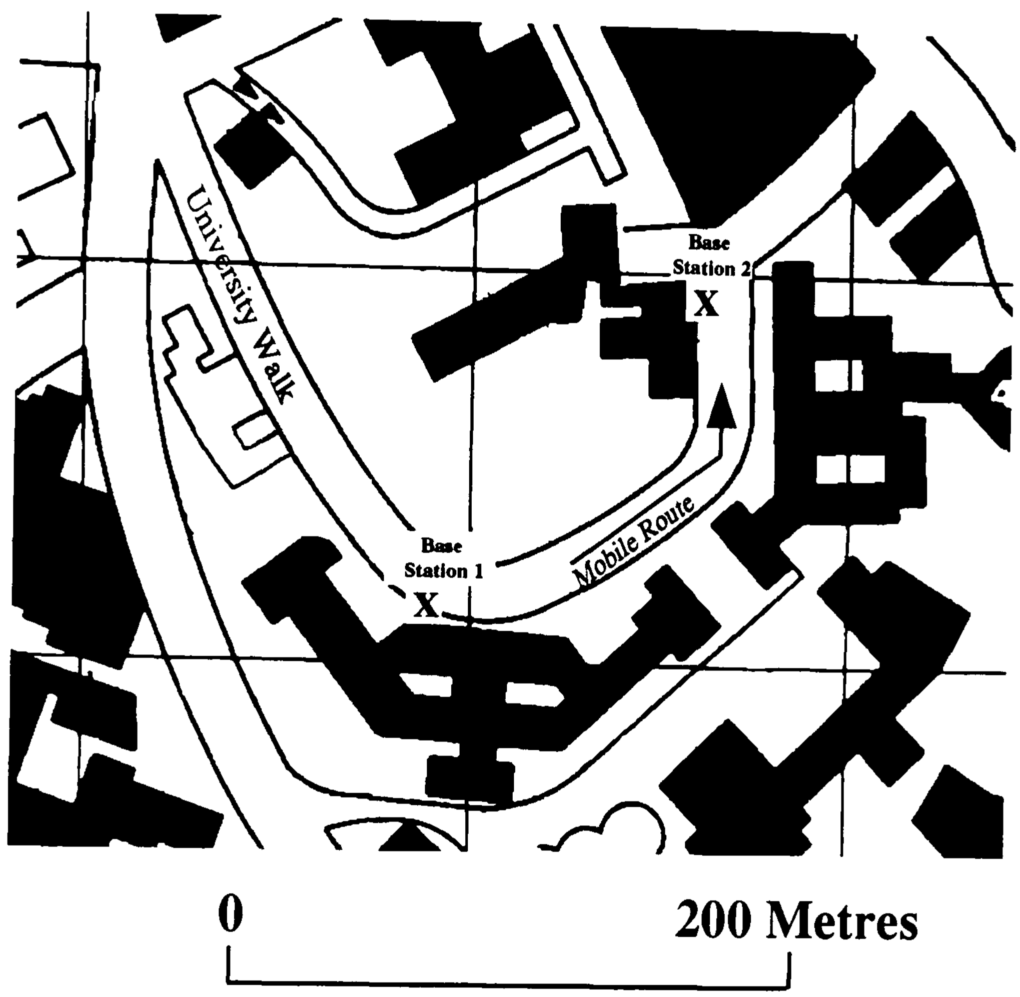

Figure 5.14: Map of University Walk

Table 5.11 gives the propagation characteristics for the environment. The RMS delay spread was found to be similar to Park Street and most likely results from the *"canyon"* effect of signal channelling along University Walk. Signal fading was also found to have a standard deviation of the order of 4.5dB for both channels, as mentioned in Section 5.4. This is only an estimate of the fading variation, as accurate extraction of fading statistics would require readings to have been averaged over many half-wavelengths (Section 5.4).

As can be seen from Figure 5.14, the corner between the two base stations is not as sharp as that in the study made in Section 5.5.1, evidenced by the smaller cross-correlation coefficient value i.e. there is less of a trend of the first base station losing the link to the mobile at the instant which the second base station becomes *visible*. Part of the reason would be due to the low wall, which would not totally block signals to the mobile as it moves out of direct LOS from base station 1, as would a building or other large solid structure.

The results of the optimised GHA analysis are presented in Tables B.9 to B.12. Again, as with the previous case study (Section 5.5.2), the application of hard handover, without any signal averaging, in most cases would require multiple handovers for the mobile unit under the conditions investigated.

The soft handover algorithm again allows for a single handover capability using the drop timer principle, with the need for a large soft handover region. However, the use of both timers provides a wide range of values which could be used to provide the single handover communications link. The shorter values of t_{Add} and t_{Drop} provide a scheme that could maintain higher SINR levels at the mobile, with reduced handover region distances.

Figure 5.15: Photograph of University Walk, Taken From Above BS1, Facing Towards BS2

Reference Signal	Threshold Δ_{Thresh}	No. H/o's	$SINR_{min}$
Pilot	8.0dB	1	12.6dB
SINR	4.0dB	1	17.2dB

Table 5.9: Optimised Hard Handover Results: Street Canyon Environment

Reference Signal	Case	Threshold Δ_{Thresh}	Timer 1 t_{Drop}	Timer 2 t_{Add}	Soft H/o Region	$SINR_{min}$
Pilot	1	5.0dB	0.85s	0.00s	66.0m	24.6dB
	2	5.0dB	0.20s	0.20s	9.0m	17.8dB
	3	0.0dB	1.65s	1.65s	0.0m	7.4dB
SINR	1	5.0→7.0dB	0.70s	0.00s	56.0m	22.7dB
	2	0.0→2.0dB	0.10s	0.10s	0.0m	12.6dB
	3	0.0→1.0dB	1.65s	1.65s	0.0m	7.4dB

Table 5.10: Optimised Soft Handover Results: Street Canyon Environment

Channel No.	Mean Delay Spread (ns)	RMS Delay Spread (ns)	10dB Window (ns)	Cross-Correlation
1	49.3	218.1	171.9	-0.409
2	49.6	261.4	191.4	

Table 5.11: Average Channel Characteristics: Street Canyon Environment

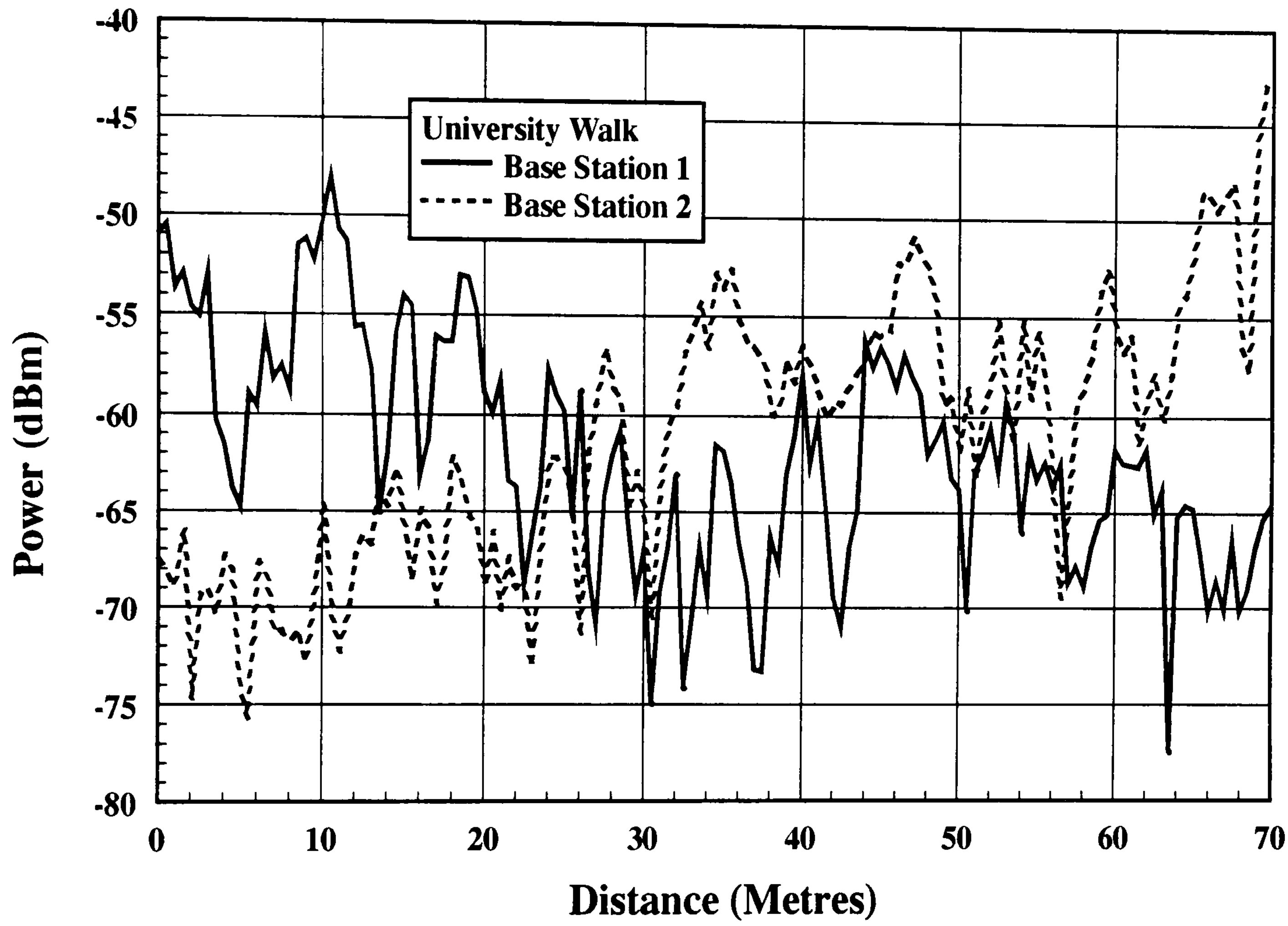

Figure 5.16: Received Pilot Signal vs. Distance: Street Canyon Environment

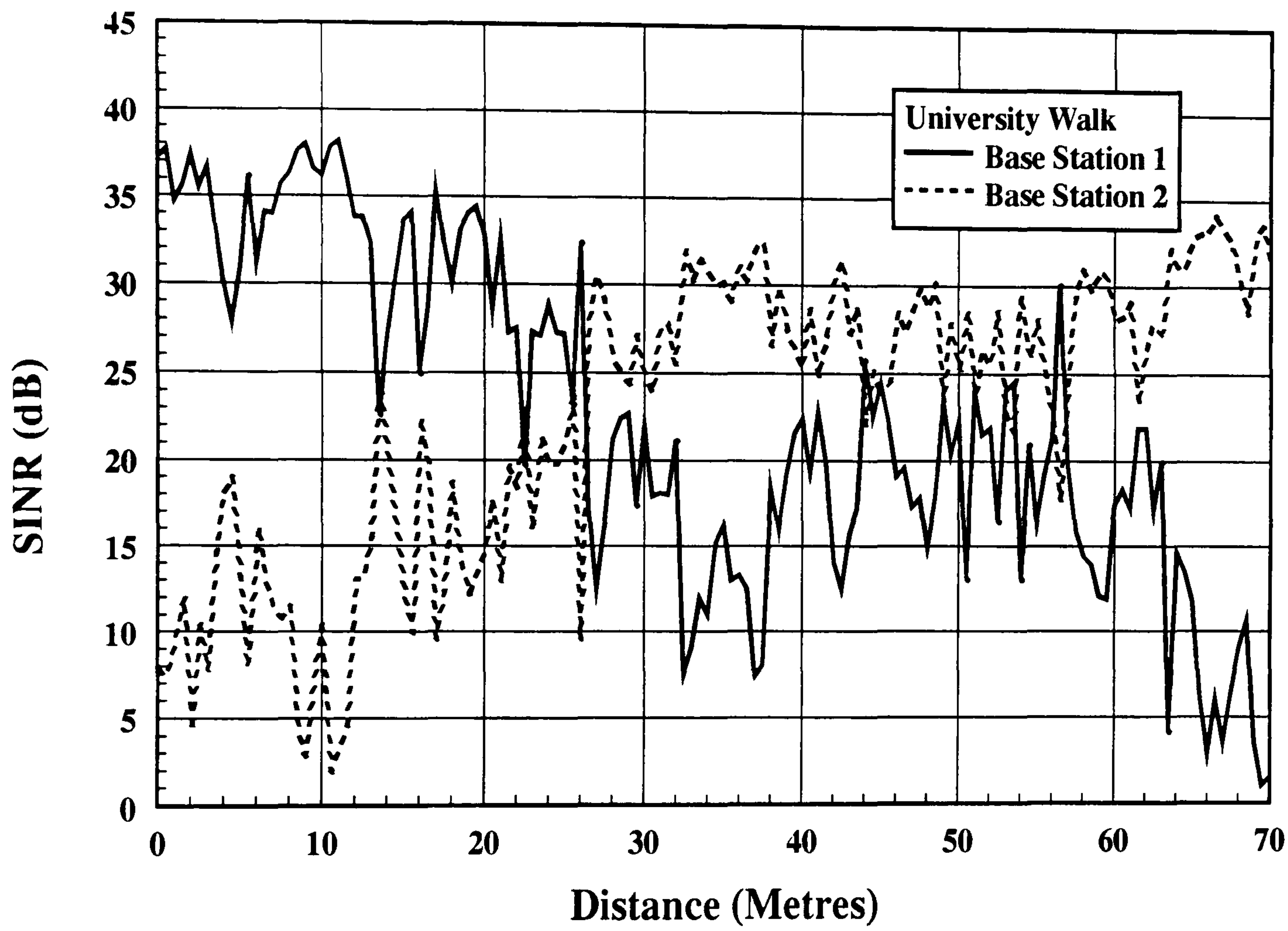

Figure 5.17: Signal-to-Interference-Noise Ratio vs. Distance: Street Canyon Environment

5.5.4 Summary of Microcell-to-Microcell Handover Analyses

Analysis has been performed on three different microcellular environments to establish handover parameter sets which comply with a set of basic system quality requirements, as defined in Section 5.2

Studies performed for hard handover have produced some notable results. In two of the scenarios, viable hard handover parameter sets have been found which comply with the system requirements defined. Comparisons of the results using the different reference signal types have shown that the SINR reference signal gives a more reliable measure on handover decisions, producing some quite significant improvements in the minimum received signal level measured at the mobile by the GHA. The comparison of these microcells shows similar trends in some respects, however there would not appear to be a set of handover criteria which can be successfully applied to all of the environments, implying that the radiowave propagation characteristics are environment-specific and not general, as has also been found by studies performed by Chia [8].

The failure of the analysis with the GHA to find a suitable parameter set for the study case of the steep urban hill environment is due mostly to the unsuitability of signal levels used and location of the base station transmitters. Alternatively, signal averaging of the situation could be considered as a way of reducing unnecessary handovers, but this would require a more detailed examination of the propagation environment, in order to establish a suitable averaging technique over the distance under investigation. It is recognised that a quick and timely handover is crucial to the way in which a user is likely to perceive the quality of the communications system [9], hence in the majority of analysed results, hard handover would not be likely to achieve this aim.

The analysis of the environments using the soft handover technique was able to find single handover parameter sets at all threshold levels examined. In contrast to the hard handover analysis, the use of the pilot reference signal appears to yield overall higher quality results, although the differences in system performance are small in many cases. Initial analysis would imply that the best system performance, related to received signal quality, can be obtained from the use of a single timer (t_{Drop}) and threshold windowing process. However, this results in lengthy handover regions and long timer periods being necessary for the single handover solution, often resulting in a handover region covering virtually the whole analysis distance. As a compromise, the use of the second timer (t_{Add}) allows a reduction of the handover region, even to zero in some cases, but with a trade-off in the minimum SINR maintained. Analysis was also performed to find the upper bound for the second timer. As can be seen from the results, this demonstrates the range of the second timer that can be applied, but with a larger penalty to the received signal level. The first timer (t_{Drop}) was not given an upper bound for the study, as the maximum value for this timer would be to extend the handover region for the entire distance of the trial. Combining signals where a large difference exists between signal strengths would not prove efficient (Section 4.3), hence the lower bound for this timer is quoted in this case.

Although optimal parameter sets can be found for each environment, it is noticeable that a common set of results has not emerged, due to the variability of propagation statistics with the scenario studied. In conclusion, it is clear that careful system planning would be required on a scenario-by-scenario basis, hence the need for a planning tool.

5.6 Macrocell-Microcell Handover Scenarios

Three studies were made of the same environment along different routes in order to examine the trade-offs possible in attempting to establish a single handover parameter set to satisfy all three situations. Figure 5.18 shows a map indicating the location of the base stations used in the study. Figure 5.19 shows a photograph of the macrocellular transmitter site, viewed facing towards the microcellular transmitter location in the distance.

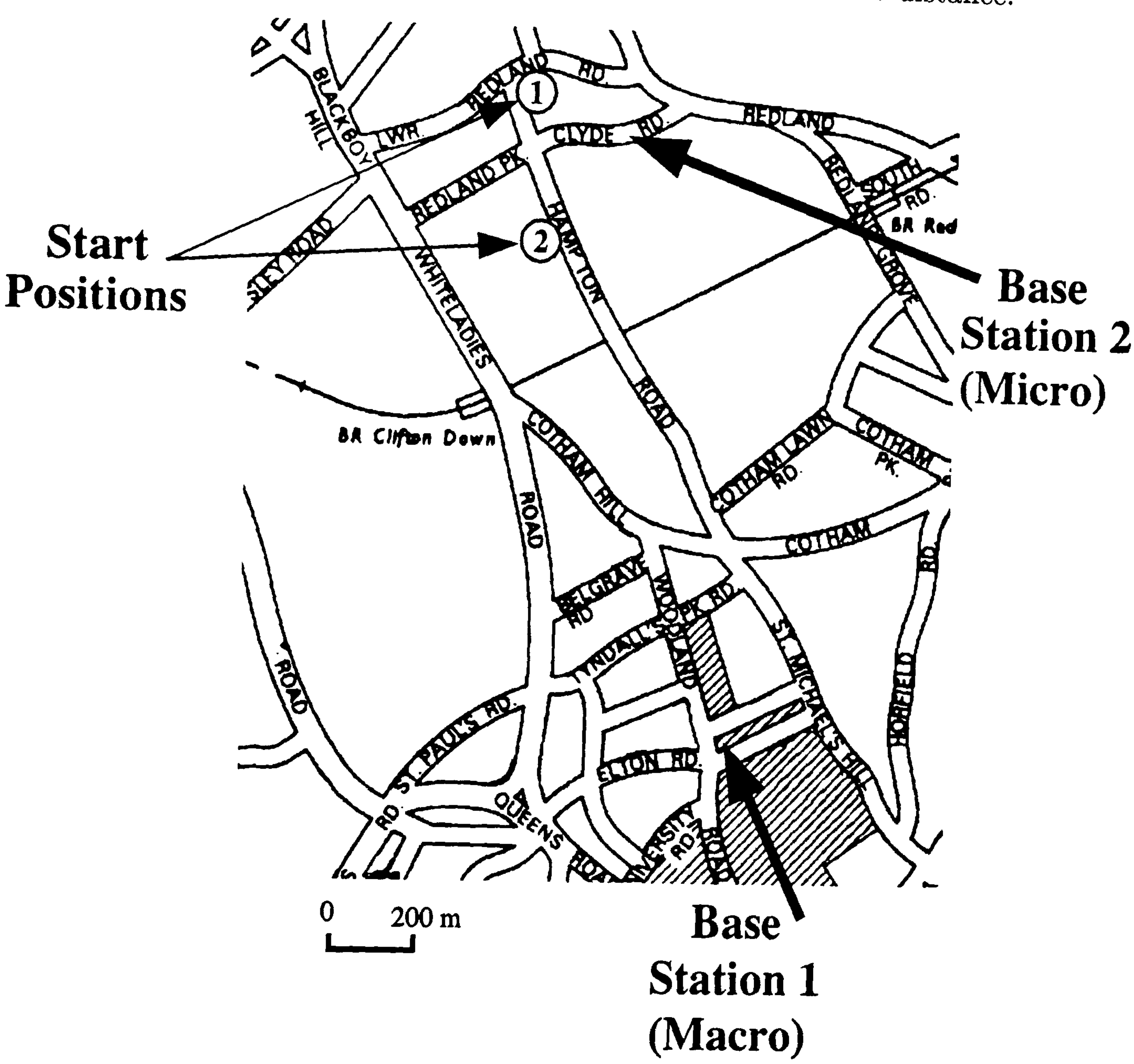

Figure 5.18: Map of the Macrocell-Microcell Study Area

The measurement scenario consisted of a *'high power'* transmitter located on the roof of a local building in a prominent geographical position to act as an umbrella or macrocellular base station and a smaller *'lower power'* transmitter, located at street level at some distance, to act as a microcellular base station. Measurements were taken along a variety of routes around the microcellular base station location and hence handover region.

The location of the macrocell base station was the roof of the University of Bristol's Senate House, a tall building on high ground with an easy direct LOS to the area of the propagation measurements, though measurements at the site may be partially obscured by local structures, particularly along the Clyde Road section of measurements. The study environment, containing the microcellular base station, was parkway along a suburban road. The buildings in the locality of the second base station consist predominantly of three storey stone-clad, terraced residential housing. Each route taken by the test vehicle is described in the relevant following sections.

The parameters for the trials were as shown in Table 5.12. Heights being measured relative to ground level and the output power measured at the output of the transmitter units. The antennas used on both the mobile test vehicle and transmitter masts were omni-directional. Further details of equipment used for the field trials are given in Section 4.11

Test Vehicle Speed	Rx Antenna Height	Tx2 Antenna Height	Tx1 Output Power	Tx2 Output Power
14mph	1.5m	3.0m	40dBm	24dBm

Table 5.12: Macrocell-to-Microcell Scenario Parameters

Figure 5.19: Photograph of the Rooftop Umbrella Cell, Viewed Facing Towards the Micro-cellular Area.

5.6.1 Macrocell-Microcell Handover: Study Case I

With reference to Figure 5.18, the first measurement route taken was on Hampton Road, heading south from point 1 for approximately 50m and turning left into Clyde Road towards transmitter 2 for a further 50m, until well within the coverage area of the second transmitter.

Figures 5.20 and 5.21 show examples of the received CIR's from both base stations. The measurement point at which these were taken is close to the turning into Clyde Road. It is worth noting the strong multipath component present in the microcellular coverage area, showing that there is a strong secondary path to the mobile from this transmitter. The path difference between these rays at this point is approximately 56m.

The signal measurements obtained from this study are presented in Figures 5.22 and 5.23. Analysis of these measurements by the GHA is presented in Tables C.1 to C.4. Table 5.15 shows the channel characteristics for this environment.

Discussion of the results presented in this section is given in Section 5.6.4.

Reference Signal	Threshold Δ_{Thresh}	No. H/o's	$SINR_{min}$
Pilot	6.0dB	1	7.0dB
SINR	7.0dB	1	13.3dB

Table 5.13: Optimised Hard Handover Results, Macrocell-Microcell: Study I

Reference Signal	Case	Threshold Δ_{Thresh}	Timer 1 t_{Drop}	Timer 2 t_{Add}	Soft H/o Region	$SINR_{min}$
Pilot	1	3.0dB	0.50s	0.00s	28.0m	14.5dB
	2	0.0dB	0.05s	0.05s	0.0m	13.3dB
	3	0.0→4.0dB	0.30s	0.30s	0.0m	7.0dB
SINR	1	8.0dB	0.55s	0.00s	29.0m	14.5dB
	2	0.0→2.0dB	0.05s	0.05s	0.0m	13.3dB
	3	0.0→8.0dB	0.30s	0.30s	0.0m	7.0dB

Table 5.14: Optimised Soft Handover Results, Macrocell-Microcell: Study Case I

Channel No.	Mean Delay Spread (ns)	RMS Delay Spread (ns)	10dB Window (ns)	Cross-Correlation
1	49.3	130.4	149.1	-0.247
2	49.2	144.6	152.7	

Table 5.15: Average Channel Characteristics, Macrocell-Microcell: Study Case I

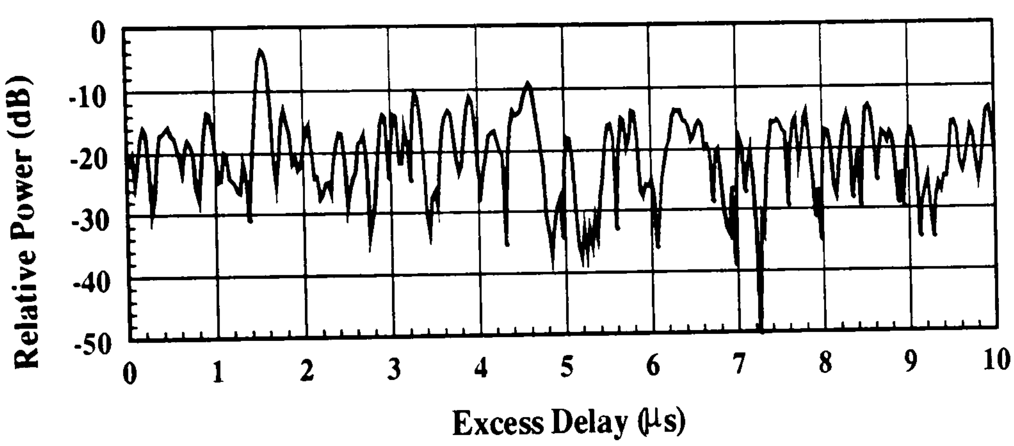

Figure 5.20: Typical CIR from Macrocellular Base Station

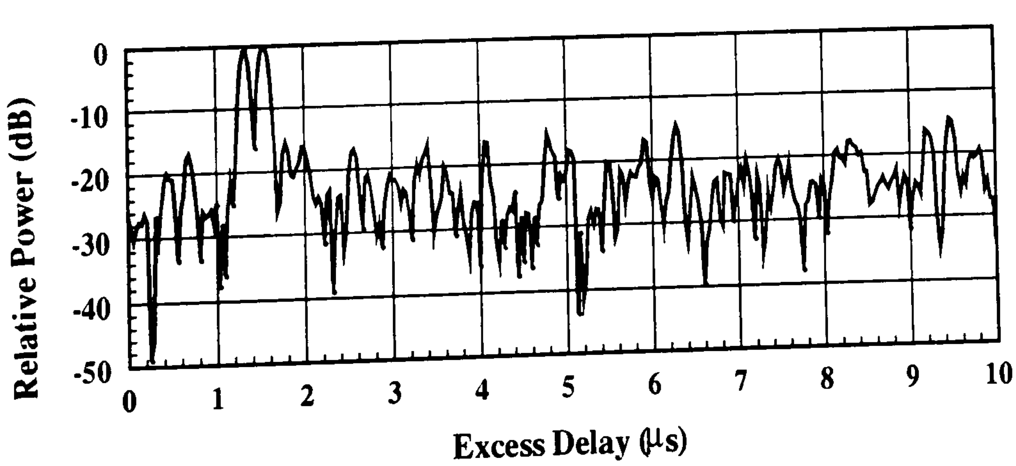

Figure 5.21: Typical CIR from Microcellular Base Station

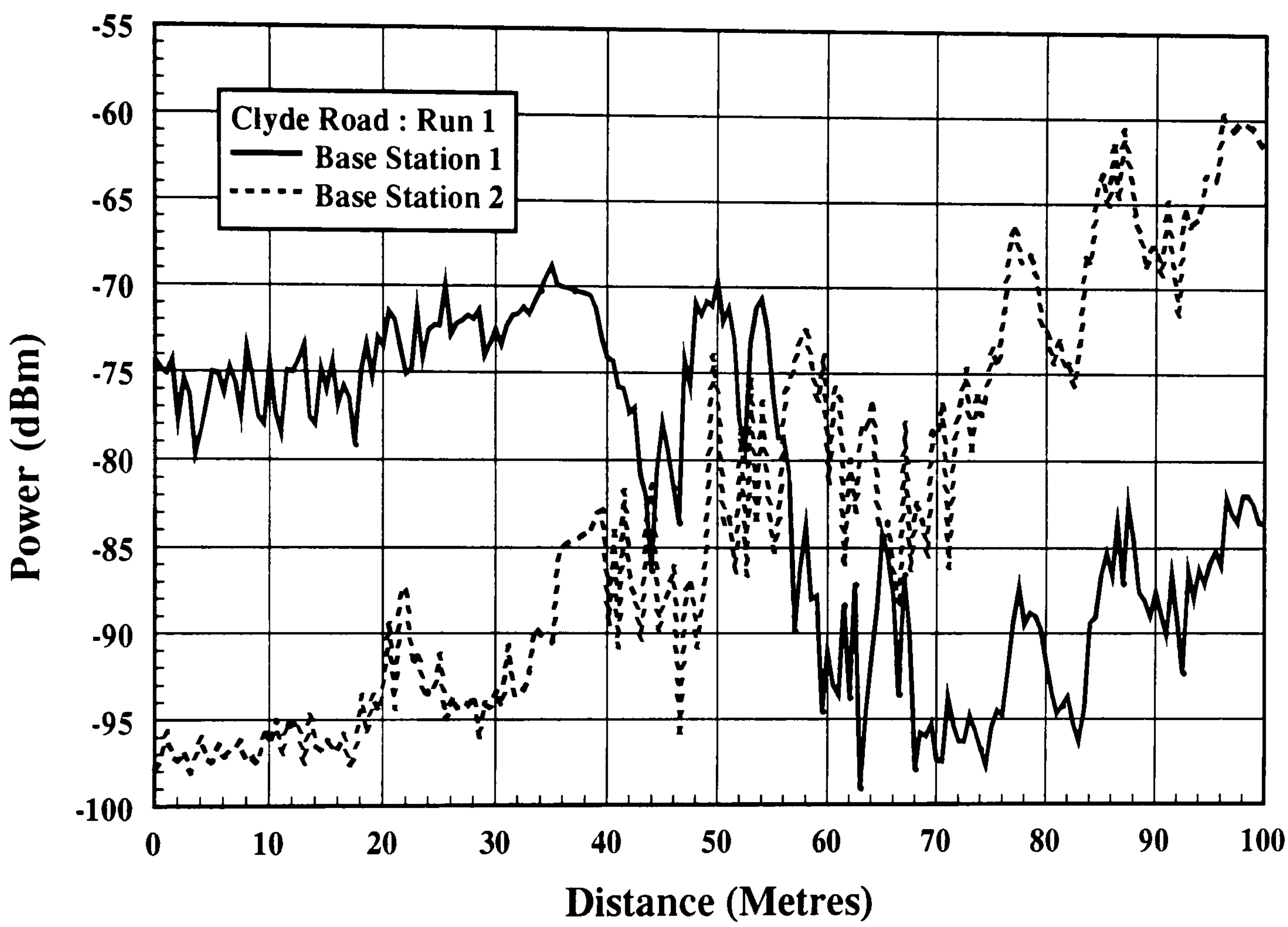

Figure 5.22: Received Pilot Signal vs. Distance, Macrocell-Microcell: Study Case I

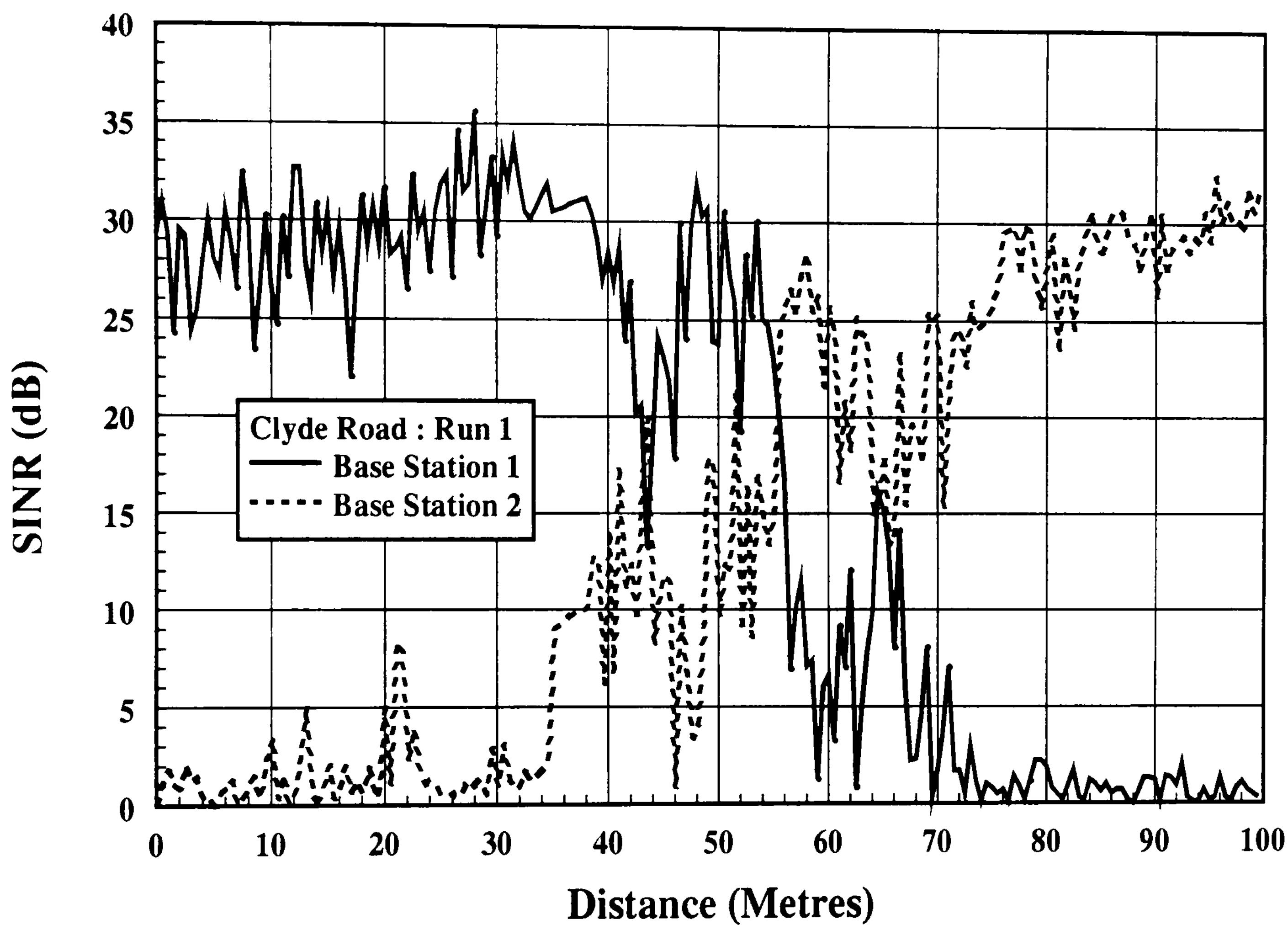

Figure 5.23: Signal-to-Interference-Noise Ratio vs. Distance, Macrocell-Microcell: Study Case I

5.6.2 Macrocell-to-Microcell Handover: Study Case II

With reference to Figure 5.18, the second measurement route taken was on Hampton Road, heading North from point 2 for approximately 50m and turning right into Clyde Road towards transmitter 2 for a further 50m, until well within the coverage area of the second transmitter.

This propagation study provides an interesting set of results in comparison to the previous case study. Figures 5.24 and 5.25 show the received pilot and SINR reference signals from the field trials. The results of the optimisation process are presented in Tables C.5 to C.8. The channel characteristics are shown in Table 5.18.

A more in-depth discussion of the results presented in this section is given in Section 5.6.4.

Reference Signal	Threshold Δ_{Thresh}	No. H/o's	$SINR_{min}$
Pilot	0.0dB	1	9.8dB
SINR	0.0dB	1	9.8dB

Table 5.16: Optimised Hard Handover Results, Macrocell-Microcell: Study Case II

Reference Signal	Case	Threshold Δ_{Thresh}	Timer 1 t_{Drop}	Timer 2 t_{Add}	Soft H/o Region	$SINR_{min}$
Pilot	1	2.0→3.0dB	0.00s	0.00s	0.5m	13.9dB
	2	2.0→3.0dB	0.00s	0.00s	0.5m	13.9dB
	3	0.0→1.0dB	0.10s	0.10s	0.0m	9.8dB
SINR	1	1.0→4.0dB	0.00s	0.00s	0.5m	13.9dB
	2	1.0→4.0dB	0.00s	0.00s	0.5m	13.9dB
	3	0.0dB	0.10s	0.10s	0.0m	9.8dB

Table 5.17: Optimised Soft Handover Results, Macrocell-Microcell: Study Case II

Channel No.	Mean Delay Spread (ns)	RMS Delay Spread (ns)	10dB Window (ns)	Cross-Correlation
1	49.7	170.1	179.7	-0.248
2	49.2	131.9	155.9	

Table 5.18: Average Channel Characteristics, Macrocell-Microcell: Study Case II

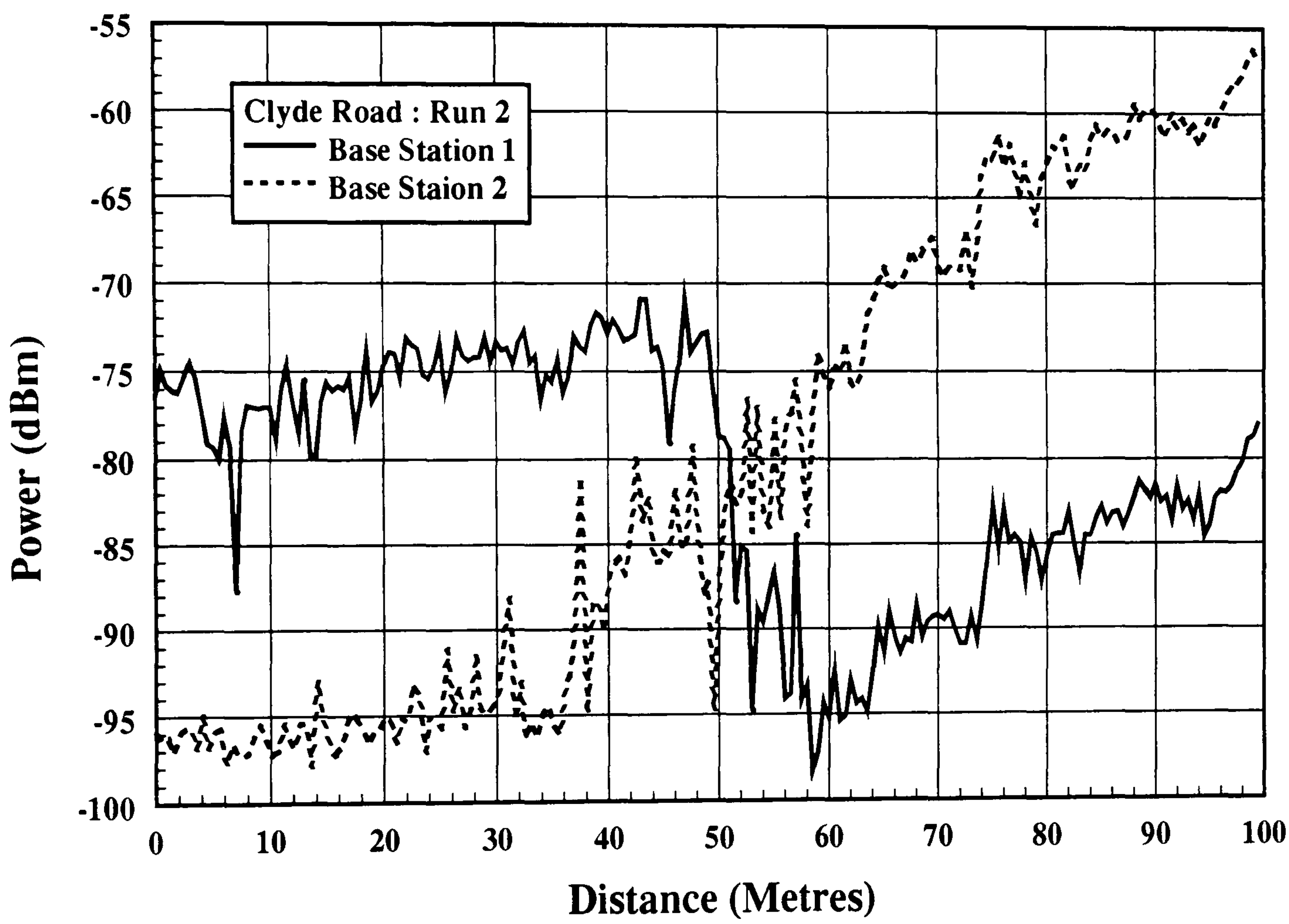

Figure 5.24: Received Pilot Signal vs. Distance, Macrocell-Microcell: Study Case II

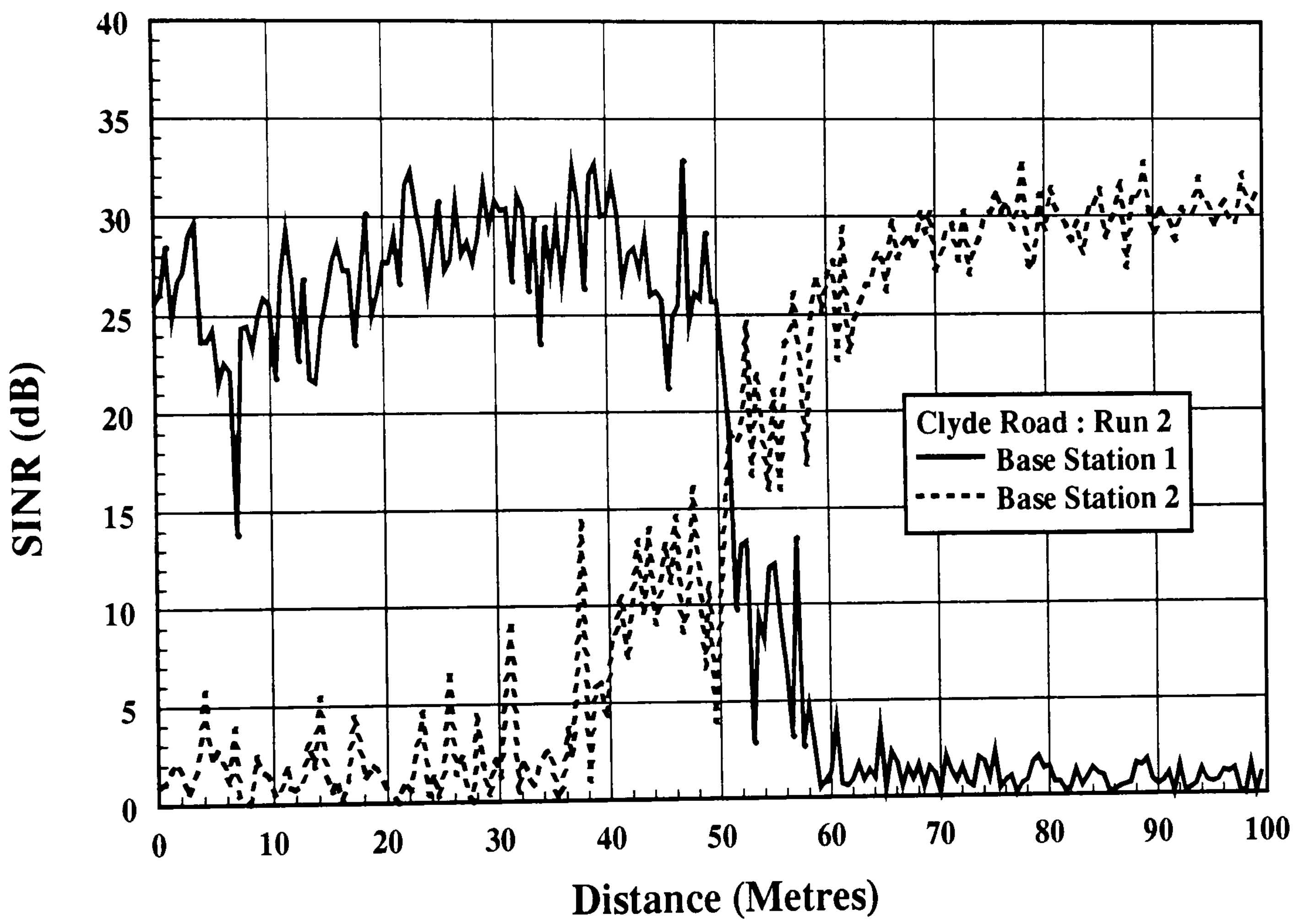

Figure 5.25: Signal-to-Interference-Noise Ratio vs. Distance, Macrocell-Microcell: Study Case II

5.6.3 Macrocell-to-Microcell Handover: Study Case III

With reference to Figure 5.18, the third measurement route taken was on Hampton Road, heading south from point 1, continuing straight-on, past the Clyde Road turning for a total distance of approximately 100m.

The channel characteristics for this route are given in Table 5.19. The received reference signals from each of the base stations are shown in Figures 5.26 to 5.27. The results of the GHA analysis for this study are presented in Tables C.9 and C.10.

The effect of these parameters on the GHA analysis of one of the other scenarios is given in Table C.11 which is the handover scenario presented in Section 5.6.1. This demonstrates the impracticality of using this set of parameters for the conditions found in the previous analysis case, as the resultant SINR minimum level is at an unacceptably low value. Hence an alternative or comprise solution will have to be sought to this situation.

Discussion of the results presented in this section is given in Section 5.6.4.

Channel No.	Mean Delay Spread (ns)	RMS Delay Spread (ns)	10dB Window (ns)	Cross-Correlation
1	49.2	113.6	139.8	-0.270
2	49.1	360.8	186.8	

Table 5.19: Average Channel Characteristics, Macrocell-Microcell: Study Case III

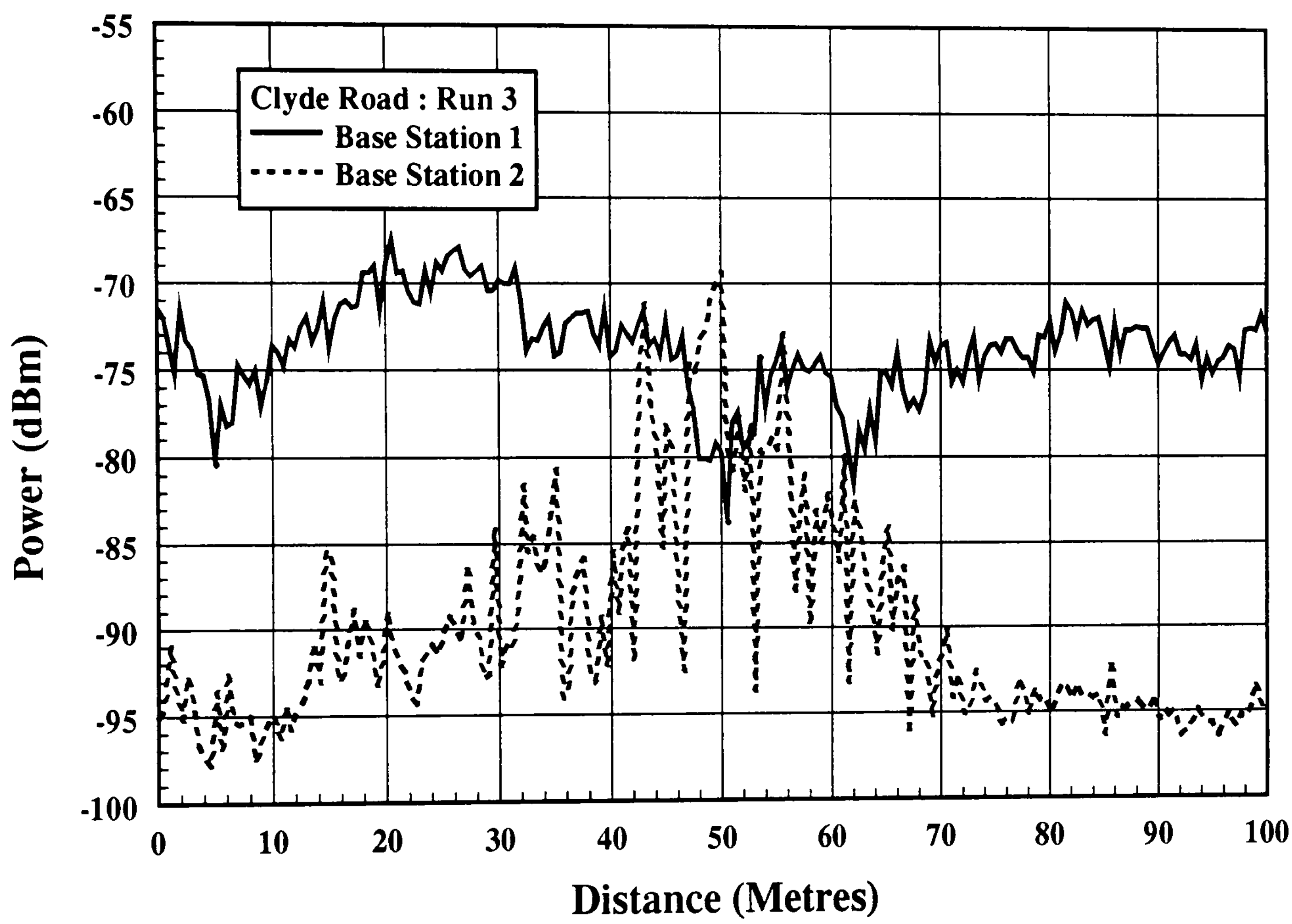

Figure 5.26: Received Pilot Signal vs. Distance, Macrocell-Microcell: Study Case III

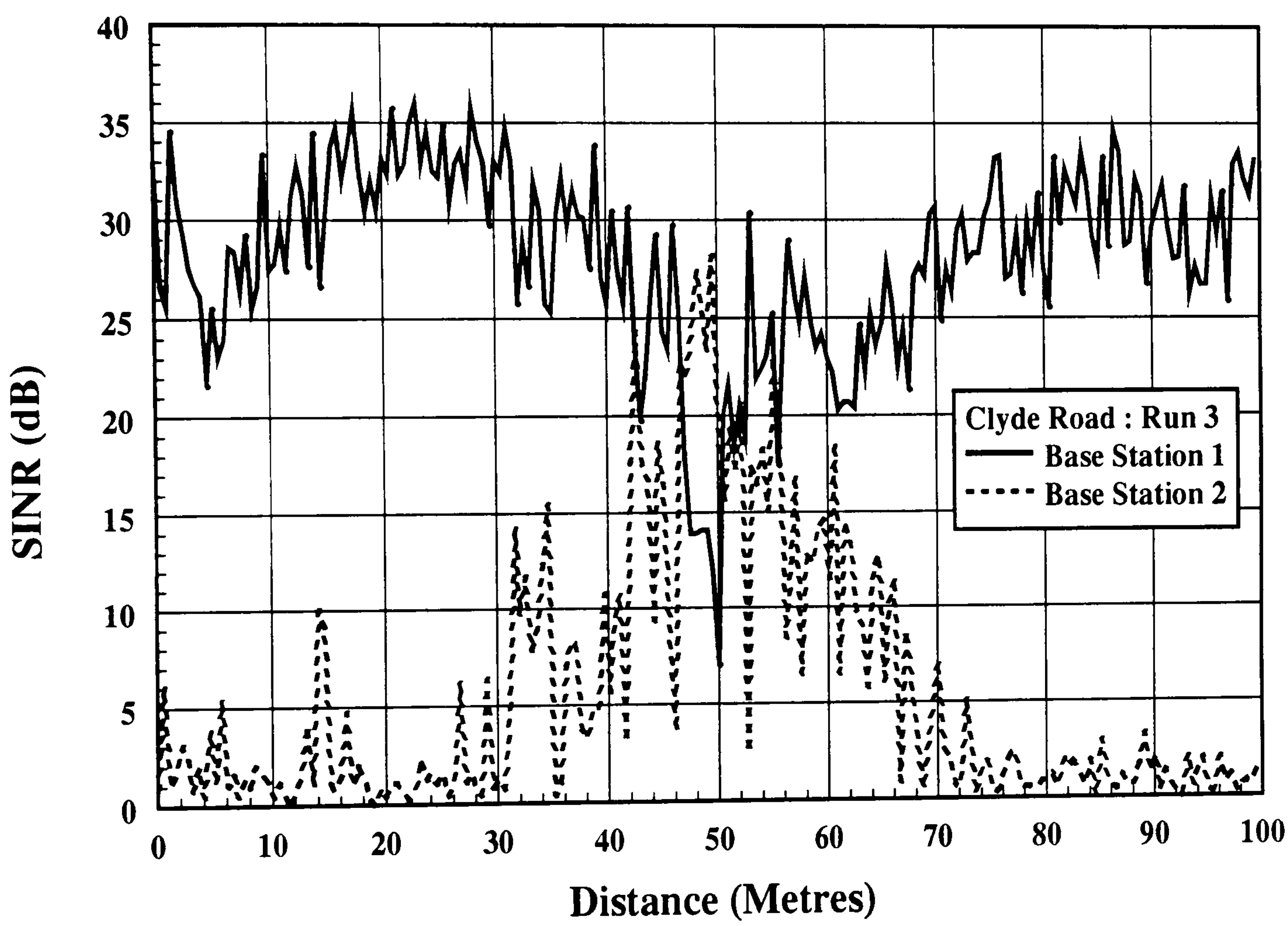

Figure 5.27: Signal-to-Interference-Noise Ratio vs. Distance, Macrocell-Microcell: Study Case III

5.6.4 Analysis of Macrocell-Microcell Handover

The study of this environment provides an interesting analysis, in that the results obtained from each of the measurement runs highlight subtle differences which affect the outcome of the GHA analysis.

5.6.4.1 Scenario Analysis

It is surprising to find the RMS delay spread of the macrocell to be, in some cases, less than that of the microcell, although this could be explained by the location of the base stations and study route taken. Geographically, Clyde Road is placed on the rising edge of a natural bowl feature of the landscape, which could easily prevent little more than LOS links with the mobile. However, in the case of the microcellular base station, signals could be reflected back from the buildings or another structure near to the junction, which is positioned such that signals from the macrocell transmitter would not be reflected. Evidence of the presence of such a structure is given in Figure 5.21 which shows the strong secondary multipath component, not present in the equivalent CIR of Figure 5.20, taken at the same measurement location.

This would also explain the very high value of the microcellular channel delay spread in the third study scenario, where relatively few values would have been taken and only at the junction to create this average. Further to this, the fading nature of the channels is visibly quite low from the plots of received signal strengths, except for the microcellular base station at the junction region. The increased fading activity in this region will have had an unavoidable bearing on the handover analyses performed.

The first two measurement scenarios were used to provide data to be analysed under the system requirements defined in Section 5.2. The individual analysis results presented show how the parameter sets can be optimised for each measurement run. Contrary to [8], where handover timing from a macrocell to a microcell is considered to be non-time critical, it is obvious that in the case studied, for a vehicular user, the handover decision must be made to avoid the imminent degradation in link quality i.e. the scenario studied is that of the microcellular base station providing coverage where the macrocell cannot[3]. The optimised analysis produces similar trends to those found in the microcellular studies (Section 5.5.4). Hard handover would appear to be able to achieve a slight margin of signal quality improvement under the SINR reference signal in the first study case, although this does require a larger threshold window to achieve a single handover scheme.

Analysis of the soft handover technique again shows how a single timer (t_{Drop}) and thresh-

[3]Of course, in all the studies presented only two base stations were used to provide coverage, in a real system coverage into this street may be given from other base stations, macrocellular or microcellular.

old system can result in an optimum signal quality system. With the use of the second timer (t_{Add}), this provides a trade-off in handover region against a minimum SINR maintained. Although, the same SINR minimum value can be established in the second case. Neither of the reference signals appears to produce any significant gains in the resultant system performance in the case of soft handover and only slight differences in the optimised parameter sets.

5.6.4.2 Proposed Combined Analysis

Cross-referencing the results of the two studies produces set of parameters which could be used to control a handover scenario for both studies i.e. a single handover parameter set for the environment, optimising the results for one of the sets already obtained. In the case of hard handover, the resulting parameter set is easily found as it must be taken as the largest value of the handover threshold in the two scenarios, which allows for a single handover. The soft handover solution is more difficult and two options are proposed to allow optimisation of the process for one of the scenarios, while the second scenario's system performance is compromised by the solution. The options proposed are:

1. The largest value found for the first timer, $t_{Drop}max$, must be used (the value for t_{Add} being 0.0s) to prevent multiple handovers and still achieve the respective $SINR_{max}$ value in both cases. The trade-off being that the compromised timer case results in a prolonged handover region.
2. If a range of values for t_{Add} exist which satisfy all three Cases, then a compromised parameter set solution can be sought.

In the scenarios studied, solutions for both options and both reference signals could be found. For hard handover the solution is 6dB and 7dB for the Pilot and SINR reference signals respectively, resulting in a $SINR_{min}$ of 9.8dB in both cases (as before).

For the soft handover case, the results are given in Table 5.20 with the resulting soft handover region and minimum SINR achieved by the system for the second scenario.

5.6.4.3 Final Scenario

The final measurement run was used to indicate the difficulties presented to a mobile which crosses the junction. Obviously, the second base station will be detected at the mobile, but ideally, handover should not occur. In the analysis of hard handover this situation is very difficult to control, only by setting a large threshold window (at least 11dB for the Pilot reference and at least 17dB for the SINR reference signals respectively) is the handover

Reference Signal	Option	Threshold Δ_{Thresh}	Timer 1 t_{Drop}	Timer 2 t_{Add}	Soft H/o Region	$SINR_{min}$
Pilot	1	3.0dB	0.50s	0.00s	144.5m	13.9dB
	2	0.0dB	0.05s	0.05s	139.0m	9.8dB
SINR	1	8.0dB	0.55s	0.00s	150.0m	13.9dB
	2	0.0→2.0dB	0.05s	0.05s	139.5m	9.8dB

Table 5.20: Optimised Soft Handover Parameter Solution Set: Macrocell-Microcell Study

avoided. A combined parameter set could not be feasibly achieved using these values in the environment under study.

Soft handover analysis provides a more realistic set of results, however, comparison of the timer values required with the ranges produced in the other analyses show that the received signal quality would be severely compromised to prevent handover under the conditions measured.

Proposed solutions to this problem are:

- Reduce the power of the microcellular base station to just below that received from the macrocellular base station at the junction, although this in itself would affect the system reliability for those mobiles requiring handover.
- Assess traffic requirements along the route and determine which of the three scenarios is most common. The system can then be optimised for that case.
- Propose an alternative microcellular base station location and re-assess the situation using the knowledge already gained from the studies performed, particularly with reference to the strong secondary multipath component from the microcellular base station in the current location.

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Chapter 6

Discussion

"Compared to the more traditional technique of hard handover, soft handover has been shown both through simulations and practical field trials, to provide for an enhanced quality communications link. However, this will only be the case if it can be incorporated into UMTS as a transparent process, both to the network and the consumer of the teleservices to be offered" C.M.Simmonds, September 1995.

6.1 Summary of Work Presented

Summary

The planning for future generation cellular systems is well under way and expected to reach deployment in the early part of the next century. Within Europe, UMTS is hoped to provide the terrestrial communications standard and through IMT-2000 it is hoped to spread further around the world, to allow a truly global roaming system. This system proposes to offer teleservices on a scale far in excess of any other cordless system to date, however, it will only be a success if it can be established in a marketable way, to satisfy the needs of both the consumer and the network operator. As such, there exists a need to develop planning tools which can aid, or assess, the implementation of such a system.

This thesis has examined the requirements and planning needs for a future cellular communications system, employing the spread spectrum technique of Direct Sequence-Code Division Multiple Access (DS-CDMA) as the air interface. This system is likely to utilise an array of cellular structures to provide the range of services proposed and as such, freedom to roam or *mobility* between these cell types is one of the key planning requirements.

True mobility can only be achieved through the use of an effective and efficient handover mechanism. Soft handover has been identified as one such handover technique, which can potentially enhance the Quality-of-Service (QoS) which a DS-CDMA system can offer, over the more commonplace technique of hard handover.

Analyses have been performed both on a theoretical basis, through the use of Monte-Carlo simulation work, as well as through practical measurement studies, with the aim of establishing an optimisation process for handover parameters to achieve a greater system performance. This chapter summarises the findings of the work and how the future development of the project should proceed.

The Future Generation Cellular Communications System

Chapter 1 summarised the development of wireless communications systems up to the envisaged future generation, high-capacity systems which are to offer users a range of services not previously available on a global basis. This summary also included discussion of the major projects involved in the development and planning of such system, namely the Universal Mobile Telecommunication System (UMTS).

Cellular Planning

The proposed cellular coverage scheme for third generation cellular systems allows a greater provision for the types of teleservice coverages required, as well as catering for the differing needs of users, be they stationary, on foot or moving at speed. Chapter 2 discussed how this novel cellular architecture has evolved and why it is required for future cellular systems. With this increase in coverage complexity comes a need to better understand the mechanisms of handover. For example, three handover systems exist: hard handover, seamless handover and the macroscopic diversity technique known as soft handover. So far only the first two techniques have been successfully implemented in operational systems, although much publicity has been made of the theoretical benefits of the latter.

One of the more important considerations made of the system is the air interface technique. Cellular communications systems have developed over the years away from the original analogue air interface techniques, to digital and higher capacity spread spectrum systems, which allow greater communications flexibility. Direct-Sequence Code Division Multiple Access has been identified as one of the leading contenders, because of the capacity and performance claims made of it, in addition to the ease of planning restrictions which it allows. The nature of DS-CDMA transmission makes implementation of the soft handover scheme relatively simple, compared with other air interface techniques and hence enables additional benefits to be gained by the system if it were taken up as the sole air interface technique.

Quality-of-Service

Having established the need for planning of a handover system and identified the techniques to be used in its implementation, measures must then be found by which the system performance can be judged and improved upon. In Chapter 3 the concept of Quality-of-Service (QoS) is discussed both from the point of view of the network operator and the standard of service offered, as perceived by the consumer. The quality measures appropriate to a DS-CDMA system utilising soft handover are discussed and further to this, a theoretical study made of a downlink communications system using a Monte-Carlo approach. This study was used to assess the effect of the handover threshold and environmental propagation statistics on the network capacity. From the studies performed in a variety of propagation environments, it was found that, in contrast to hard handover, the capacity of a soft handover system could be increased by using a larger threshold window, achieving an optimum capacity with a threshold value in the range 4dB to 6dB. The results of this simulation study are shown in Figures 3.12 to 3.14.

Handover Mechanisms

However, a theoretical gain in system capacity, based on the control of the handover threshold, may not be sustainable in a practical cellular environment. For this reason it is necessary to perform field trials and assess the requirements of that environment to test the viability of the handover schemes. Chapter 4 gives the background to the Fast Fourier Transform dual-channel sounder system developed for this purpose. The system allows simultaneous reception of signals from two separate base station transmitters at a mobile receiver unit. Measurements can thus be made in a variety of handover scenarios and the data obtained from these studies post-processed and analysed.

A generic handover algorithm (GHA) is proposed, which enables the handover analysis of the data obtained from cellular field trials. The basis of the algorithm is to maintain a communications link to the mobile from the available base stations, via membership of an Active Set. Membership of this set is determined by the application of handover initiation and termination timers, as well as a threshold level which is set relative to the maximum received signal strength.

The GHA allows analysis of three handover techniques: hard handover, soft handover and switched diversity. The performance of the handover schemes under different parameters for the same environment is assessed in terms of: number of handover attempts, size of the handover region (in the case of soft handover) and the signal-to-interference-noise ratio (SINR) at the mobile unit determined by the GHA. The cumulative signal power received by the mobile under any scheme can also be judged, relative to the maximum received cumulative signal level produced by the continuous combination of all base station's signals, as a measure of effective use of all the available energy.

Optimisation of Handover Parameters

In Chapter 5, results are presented for the studies of three microcellular handover environments and one macrocellular-to-microcellular environment. Each study was chosen as representative of different features of a third generation mixed cell handover scenario. Each scenario was assessed using the GHA algorithm, to find the sets of parameters which would optimise the system handover performance according to a series of system requirements and signal quality measures as follows:

1. Attempt to establish the parameters for a single handover system.
2. Maximise the received Signal-to-Interference-Noise Ratios (SINR's) for a handover technique.
3. Maximise the theoretical system capacity.
4. Minimise signalling load in the network.

According to the analyses performed, it was found that the optimum microcellular performance could be achieved using soft handover and a single timer approach. It was found that the signal reference type, either received signal strength or SINR, had little bearing on the soft handover process, though slight improvements in performance were possible for hard handover using the SINR reference. It was also found that the propagation statistics between the microcellular environments varied so much that it may not be possible to find a common set of parameters to achieve optimal handover implementation for all scenarios. However, the technique was shown to be a more versatile handover technique, with the ability to almost pre-empt the handover region, preventing received signal levels from degrading as low as those under the hard handover scheme in the same environmental conditions.

The handover drop timer, t_{Drop}, delays termination of the handover process until signal degradation on the *old* link is firmly established. However, long handover periods will in turn affect the network signalling requirements and system signalling redundancy. A compromise system could be achieved through the use of a second timer (t_{Add}), which delays handover initiation to a point where signal improvement on the *new* link is established, resulting in a link trade-off of handover region length with the minimum SINR achieved in the environment.

In the case of the macrocellular-to-microcellular handover scenario, three studies were performed along different routes within the same environment. The first two handover scenarios were used to establish whether a single set of parameters could be established for both cases, and to further validate the measurement and analysis process. Solutions could be sought for both hard and soft handover techniques. However, soft handover was found to be capable of maintaining a higher quality link with a single timer and threshold principle, though a compromise solution with shorter handover period could be sought, which achieved the same performance measures as hard handover. Although from the capacity studies made and the high hard handover threshold required, it is likely that this would negate any benefits this simpler technique would have to offer.

The third study was used as a null-handover case, where the parameters necessary to prevent an unnecessary handover of a transient mobile in the microcellular coverage area were established. It was found that a viable solution could not be found from the data obtained in the field trials, which would allow the derivation of a single handover parameter set for all three cases. The failure of this aspect of the analysis was due to the propagation statistics and base station placement, not the analysis system used, showing the importance of the analysis procedure in the handover technique's assessment. A proposal was then made for a re-assessment of the situation based on the results already obtained.

6.2 Future Work

The capacity for the further development of this work cannot easily be quantified. Developments and proposals for the third generation cellular systems are still being drawn-up, developed and tested, as outlined in Chapter 1. However, four areas of improvement can be considered.

System Simulation

The simulation used to establish the capacity of a network under different handover schemes should be extended to investigate the following features:

- The effect on system performance of the handover timers, t_{Add} and t_{Drop} with the movement of the users within the environment e.g. at different speeds.
- Different service requirements i.e. minimum link qualities required to support the variety of different services proposed under UMTS.
- Cell overlay systems i.e. microcells overlayed by a macrocell.

Field Trial Databases and System Evaluation

The GHA relies on the availability of propagation data, simultaneously received from multiple base stations. This could be obtained from a variety of sources e.g. further field trials using the FFT dual-channel sounder system, or a propagation simulation tool, such as that under development by Anthanasiadou et al. at Bristol University [1]. The combination of these two sources could be used to greatly enhance the versatility of the algorithm in cellular planning. Propagation tools can be used to give estimates of the propagation environment and optimise the location of base stations. Field trials based on these findings and analysis of the propagation data obtained could then be used to confirm the logistics of the installation.

Handover Protocols

As indicated in Chapter 2, the full impact of the soft handover technique on the signalling performance of a system cannot be accurately assessed until the protocol of that system is developed. Soft handover can be simulated and shown to be beneficial to a system's capacity and provide for improvements in quality-of-service, if it can be implemented as a transparent process within the network. Intuitively, soft handover produces signalling redundancy, since it requires the same information to be transmitted via more than one link during handover. This will only be of benefit if the network can support this additional loading, without a loss in the perceived quality of the service to the user.

Quality Measures

The quality measures used to assess communications links so far have concentrated on providing for a minimum signal level, based on a theoretical performance requirement for a voice system. Once in production, system quality will be judged by the consumers of the teleservices. With such an abundance of services to be offered, a single minimum signal requirement for reliable operation of a link may prove to be insufficient and a more perceptive measure will have to be found for each service, based on a proposed production model's performance.

6.3 Concluding Remarks

The handover process is an integral and vital part of the cellular communications process, it is only through the optimum implementation of a handover scheme that the future generation communications systems will achieve their aim of a truly global roaming service.

The work presented in this thesis has considered the development and evaluation of tools to aid planning of a future generation downlink communications system incorporating soft handover. The evaluation technique and parameter optimisation process has been studied with a view to improving system quality. Compared to the more traditional technique of hard handover, soft handover has been shown both through simulations and practical field trials, to provide for a greater quality communications link. However this will only be the case if it can be incorporated into UMTS as a transparent process both to the network and consumer of the teleservices offered.

References

[1] G. E. Athanasiadou, A. R. Nix, and J. P. McGeehan, "A New 3D Indoor Ray-Tracing Propagation Model with Particular Reference to the Prediction of Power and Delay Spread," in *6th International Symposium on Personal, Indoor and Mobile Communications (PIMRC'95)*, (Toronto, Canada), pp. 1161–1165, IEEE, September 1995.

Appendix A

FFT Channel Sounder Modes of Operation

A.1 STORE ONLY Mode

In STORE ONLY mode, the mobile receiver captures and stores data to disk at regular intervals. The distance between measurement points can be specified in units of 0.5 metres, the channel sounder using a calibrated pulse generator attached to the vehicle (80 pulses produced every 1 metre).

The flow chart for the STORE ONLY program module is shown in Figure A.1. The received data samples (16-bit words) are retrieved from the VME memory in quadrature (I and Q) format. The channel data are transferred to the hard drive together with the associated data capture information to be stored in a file header. This header contains the following information to be used later by the OFFLINE mode of operation (See Section A.2).

- Data logging mode i.e. STORE ONLY.
- Chip Rate
- Sample Period
- Trigger mode
- Measurement Interval
- Data file name
- Number of measurement points
- PN sequence type.

After the header, the quadrature data for each measurement point and channel is then stored along with the time of data capture.

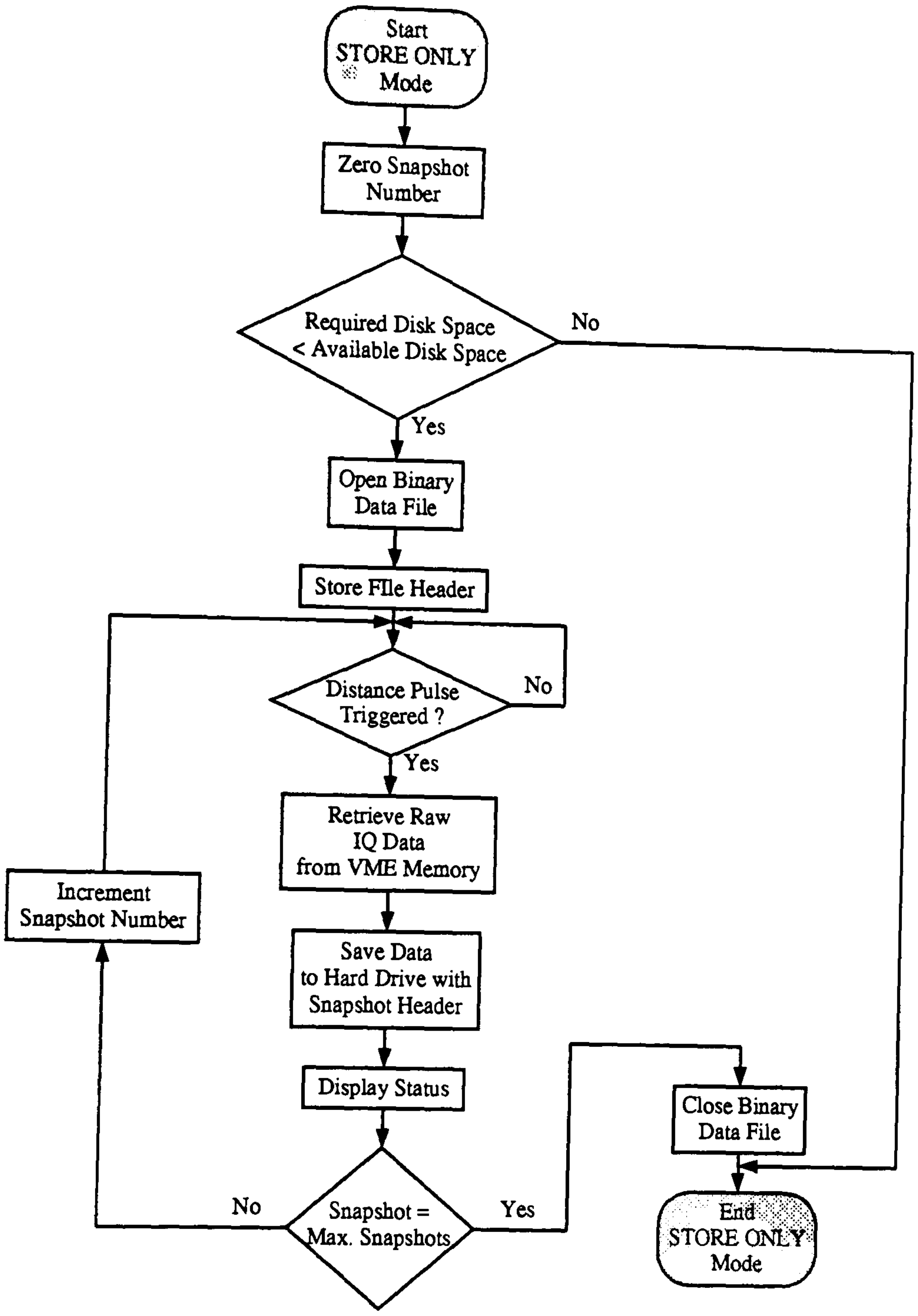

Figure A.1: Flow Chart for the Receiver STORE ONLY Mode

A.2 OFFLINE ONLY Mode

In OFFLINE ONLY mode, the stored data obtained from a STORE ONLY mode operation is retrieved from disk. The data is correlated with two stored PN sequences to produce CIRs for both channels.

The flow chart for the DISPLAY only program module is shown in Figure A.2. The program retrieves the quadrature (I and Q) data or the raw data samples stored on disk and writes them to the VME memory. After the DSP module (shown as the dashed box in Figure A.2) processes the data, the program retrieves the channel impulse response data samples for both channels. The resultant CIRs are displayed on the VDU screen and also stored to disk for further analysis by the Generic Handover Algorithm (See Section 4.10)

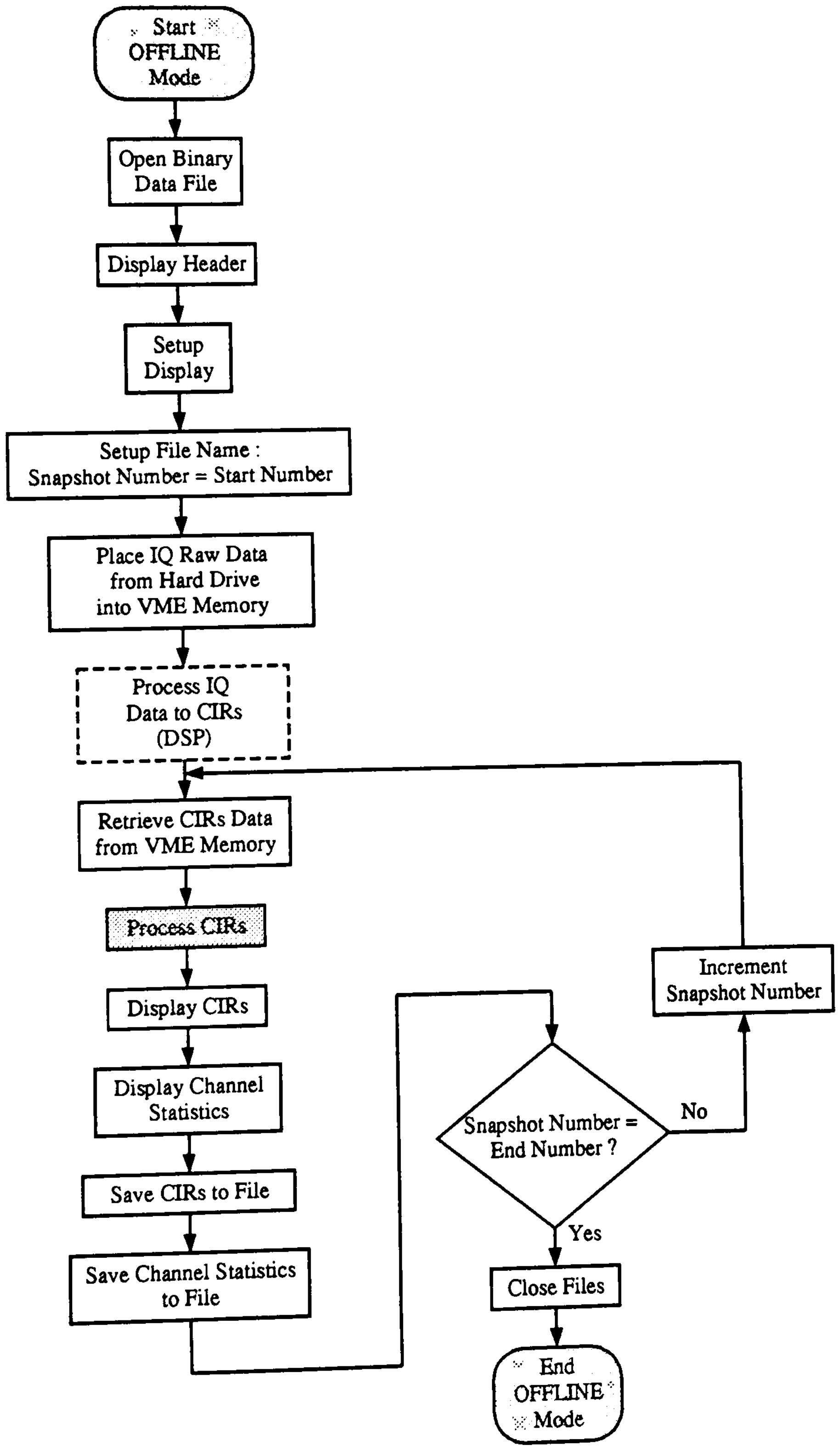

Figure A.2: Flow Chart for the Receiver OFFLINE Mode

A.3 DISPLAY ONLY Mode

In DISPLAY ONLY mode, data is continuously captured, processed and displayed without storing to disk in the interim. Data capture can be triggered by pulsed input from a pulse generator or by an internal timer. The captured data is correlated with two stored PN sequences to produce CIRs for both channels. The resultant CIRs for both channels are displayed on the VDU screen of the receiver.

The flow chart for the DISPLAY only program module is shown in Figure A.3. The program retrieves the channel impulse response data samples from the VME memory for both CIRs.

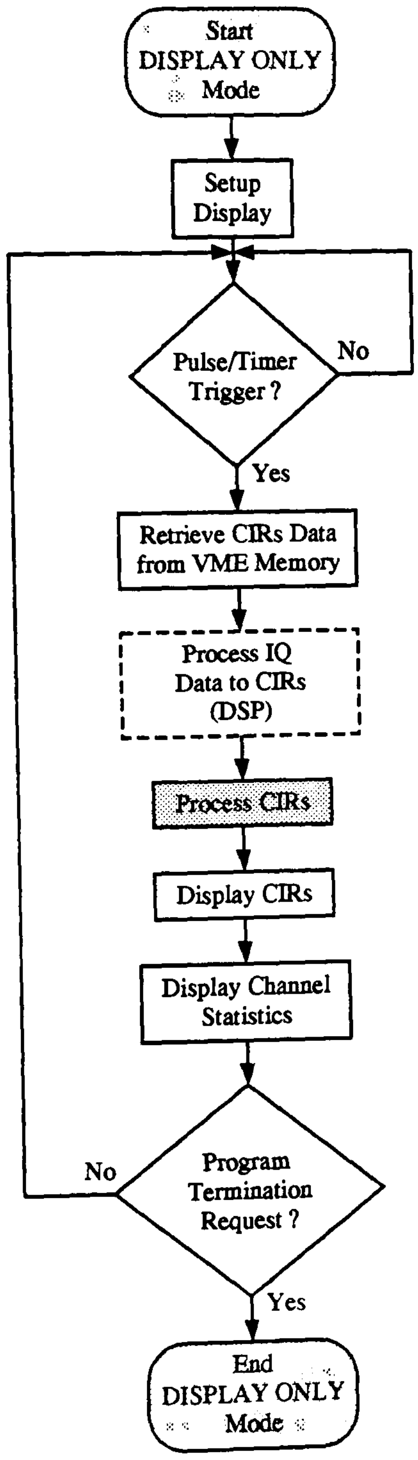

Figure A.3: Flow Chart for the Receiver DISPLAY ONLY Mode

Appendix B

Optimised Handover Results from Microcellular Field Trials

B.1 Street-Corner Handover

Threshold Δ_{Thresh} (dB)	No. Handover Attempts	Total Distance (m)	First Handover @ (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	1	0.0	19.5	6.8	99.44
1.0	1	0.0	19.5	6.8	99.44
2.0	1	0.0	19.5	6.8	99.44
3.0	1	0.0	19.5	6.8	99.44
4.0	1	0.0	19.5	6.8	99.44
5.0	1	0.0	19.5	6.8	99.44
6.0	1	0.0	19.5	6.8	99.44
7.0	1	0.0	19.5	6.8	99.44
8.0	1	0.0	19.5	6.8	99.44

Table B.1: Hard Handover Using Pilot Reference: Street-Corner Handover

Threshold Δ_{Thresh} (dB)	No. Handover Attempts	Total Distance (m)	First Handover @ (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0	3	3.0	16.0	8.0	99.65
1	3	3.0	16.0	8.0	99.65
2	1	0.0	19.0	16.9	99.58
3	1	0.0	19.0	16.9	99.58
4	1	0.0	19.5	6.8	99.44
5	1	0.0	19.5	6.8	99.44
6	1	0.0	19.5	6.8	99.44
7	1	0.0	19.5	6.8	99.44
8	1	0.0	19.5	6.8	99.44

Table B.2: Hard Handover Using SINR Reference: Street-Corner Handover

Threshold Δ_{Thresh} (dB)	Timer 1 t_{Drop} (s)	Timer 2 t_{Add} (s)	Handover Start (m)	Handover Region (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	0.00	0.00	19.5	0.0	6.8	99.44
	0.00	0.00	19.5	0.0	6.8	99.44
	0.00	0.00	19.5	0.0	6.8	99.44
1.0	0.30	0.00	16.0	6.5	19.0	99.83
	0.30	0.00	16.0	6.5	19.0	99.83
	-	-	-	-	-	-
2.0	0.25	0.00	16.0	6.0	19.0	99.83
	0.05	0.05	19.5	0.5	6.8	99.44
	0.05	0.05	19.5	0.5	6.8	99.44
3.0	0.25	0.00	16.0	6.0	19.0	99.83
	0.05	0.05	19.5	0.5	6.8	99.44
	0.05	0.05	19.5	0.5	6.8	99.44
4.0	0.25	0.00	16.0	6.0	19.0	99.83
	0.05	0.05	19.5	0.5	6.8	99.44
	0.05	0.05	19.5	0.5	6.8	99.44
5.0	0.65	0.00	9.0	17.0	19.0	99.91
	0.05	0.05	19.5	0.5	6.8	99.44
	0.05	0.05	19.5	0.5	6.8	99.44
6.0	0.65	0.00	9.0	17.0	19.0	99.91
	0.05	0.05	19.5	0.5	6.8	99.44
	0.05	0.05	19.5	0.5	6.8	99.44
7.0	0.65	0.00	5.0	21.0	19.0	99.96
	0.05	0.05	19.5	0.5	6.8	99.44
	0.05	0.05	19.5	0.5	6.8	99.44
8.0	0.65	0.00	3.5	22.5	19.8	99.99
	0.05	0.05	19.5	0.5	6.8	99.44
	0.05	0.05	19.5	0.5	6.8	99.44

Table B.3: Optimised Soft Handover Using Pilot Reference: Street-Corner Handover

Threshold Δ_{Thresh} (dB)	Timer 1 t_{Drop} (s)	Timer 2 t_{Add} (s)	Handover Start (m)	Handover Region (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	0.25	0.00	16.0	5.5	19.0	99.83
	0.05	0.05	19.5	0.0	6.8	99.44
	0.05	0.05	19.5	0.0	6.8	99.44
1.0	0.25	0.00	16.0	5.5	19.0	99.83
	0.05	0.05	19.5	0.0	6.8	99.44
	0.05	0.05	19.5	0.0	6.8	99.44
2.0	0.25	0.00	16.0	5.5	19.0	99.83
	0.05	0.05	19.5	0.0	6.8	99.44
	0.05	0.05	19.5	0.0	6.8	99.44
3.0	0.25	0.00	16.0	5.5	19.0	99.83
	0.05	0.05	19.5	0.0	6.8	99.44
	0.05	0.05	19.5	0.0	6.8	99.44
4.0	0.25	0.00	16.0	6.0	19.0	99.83
	0.05	0.05	19.5	0.5	6.8	99.44
	0.05	0.05	19.5	0.5	6.8	99.44
5.0	0.25	0.00	16.0	6.0	19.0	99.83
	0.05	0.05	19.5	0.5	6.8	99.44
	0.05	0.05	19.5	0.5	6.8	99.44
6.0	0.65	0.00	9.0	17.0	19.0	99.91
	0.05	0.05	19.5	0.5	6.8	99.44
	0.05	0.05	19.5	0.5	6.8	99.44
7.0	0.65	0.00	5.0	21.0	19.0	99.96
	0.05	0.05	19.5	0.5	6.8	99.44
	0.05	0.05	19.5	0.5	6.8	99.44
8.0	0.65	0.00	5.0	21.0	19.0	99.96
	0.05	0.05	19.5	0.5	6.8	99.44
	0.05	0.05	19.5	0.5	6.8	99.44

Table B.4: Optimised Soft Handover Using SINR Reference: Street-Corner Handover

B.2 Microcell-Microcell Handover: Steep Hill Environment

Threshold Δ_{Thresh} (dB)	No. Handover Attempts	Total Distance (m)	First Handover @ (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	61	203.5	9.0	6.1	97.70
1.0	37	203.5	9.0	9.2	98.06
2.0	27	197.0	9.0	9.2	98.18
3.0	23	197.5	9.0	9.2	98.14
4.0	19	143.5	63.0	9.2	98.10
5.0	13	55.5	66.0	9.2	97.79
6.0	9	55.0	66.5	9.2	97.38
7.0	5	36.0	85.5	9.2	97.02
8.0	5	40.5	85.5	9.2	96.34

Table B.5: Hard Handover Using Pilot Reference: Steep Hill Environment

Threshold Δ_{Thresh} (dB)	No. Handover Attempts	Total Distance (m)	First Handover @ (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	35	182.5	30.0	6.1	98.35
1.0	23	149.5	63.0	9.2	98.31
2.0	17	54.5	63.0	9.2	98.26
3.0	15	54.5	63.0	9.2	98.23
4.0	13	54.5	63.0	9.2	98.20
5.0	11	52.0	66.0	9.2	98.07
6.0	11	52.0	66.0	9.2	98.03
7.0	11	52.0	66.0	9.2	98.05
8.0	7	33.0	85.0	9.2	97.52

Table B.6: Hard Handover Using SINR Reference: Steep Hill Environment

Threshold Δ_{Thresh} (dB)	Timer 1 t_{Drop} (s)	Timer 2 t_{Add} (s)	Handover Start (m)	Handover Region (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	4.95	0.00	9.0	241.0	17.7	99.99
	0.20	0.20	112.5	0.0	9.2	97.15
	0.60	0.60	126.5	0.0	6.4	96.02
1.0	4.95	0.00	9.0	241.0	17.7	99.99
	0.30	0.30	123.0	0.5	10.0	96.71
	0.65	0.65	126.5	0.5	6.4	96.02
2.0	4.95	0.00	9.0	241.0	17.7	99.99
	0.30	0.30	113	10.5	10.0	97.46
	0.65	0.65	126.5	0.5	6.4	96.02
3.0	2.95	0.00	9.0	241.0	17.7	99.99
	0.30	0.30	113.0	13.0	10.0	97.42
	1.15	1.15	126.0	8.5	10.0	96.18
4.0	2.90	0.00	9.0	241.0	17.7	99.99
	0.30	0.30	113.0	13.0	10.0	97.47
	1.15	1.15	126.0	8.5	10.0	96.18
5.0	2.90	0.00	7.5	242.5	17.7	100.00
	0.40	0.40	118.5	8.5	10.0	97.16
	1.15	1.15	126.0	8.5	10.0	96.18
6.0	2.60	0.00	7.5	242.5	17.7	100.00
	0.30	0.25	65.0	64.0	16.0	99.16
	1.15	1.15	126.0	11.5	10.0	96.18
7.0	2.05	0.00	7.5	242.5	17.7	100.00
	0.45	0.45	66.5	64.0	14.4	99.16
	1.15	1.15	126.0	20.5	10.0	96.18
8.0	1.90	0.00	7.5	242.5	17.7	100.00
	0.65	0.65	68.5	64.0	14.4	99.08
	1.15	1.15	126.0	124.0	10.0	96.18

Table B.7: Optimised Soft Handover Using Pilot Reference: Steep Hill Environment

Threshold Δ_{Thresh} (dB)	Timer 1 t_{Drop} (s)	Timer 2 t_{Add} (s)	Handover Start (m)	Handover Region (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	6.20	0.00	30.0	220.0	17.7	99.94
	0.25	0.25	112.5	0.0	9.2	97.15
	0.60	0.60	126.5	0.0	6.4	96.02
1.0	5.00	0.00	30.0	220.0	17.7	99.94
	0.35	0.30	112.5	0.5	9.2	97.15
	0.6	0.6	126.5	0.0	6.4	96.02
2.0	5.00	0.00	30.0	220.0	17.7	99.94
	0.35	0.30	113.0	11.0	10.0	97.46
	0.90	0.90	126.5	3.0	6.4	99.02
3.0	4.95	0.00	30.0	220.0	17.7	99.94
	0.35	0.30	113.0	11.0	10.0	97.46
	0.90	0.90	126.5	3.0	6.4	96.02
4.0	4.65	0.00	30.0	220.0	17.7	99.94
	0.35	0.30	113.0	13.5	10.0	97.46
	0.90	0.90	126.5	5.5	6.4	96.02
5.0	4.65	0.00	30.0	220.0	17.7	99.94
	0.40	0.40	121.0	6.0	10.0	96.47
	0.95	0.95	126.5	6.0	6.4	96.02
6.0	3.05	0.00	30.0	217.0	17.7	99.94
	0.45	0.20	64.5	63.0	16.0	97.00
	1.15	1.15	126.0	8.5	10.0	96.02
7.0	3.05	0.00	9.0	241.0	17.7	99.99
	0.35	0.25	65.0	61.5	16.0	99.16
	1.15	1.15	126.0	8.5	10.0	96.18
8.0	2.95	0.00	9.0	241.0	17.7	99.99
	0.30	0.30	65.5	61.5	16.0	99.15
	1.15	1.15	126.0	9.5	10.0	96.18

Table B.8: Optimised Soft Handover Using SINR Reference: Steep Hill Environment

B.3 Microcell-Microcell Handover: Street Canyon Environment

Threshold Δ_{Thresh} (dB)	No. Handover Attempts	Total Distance (m)	First Handover @ (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	15	43.5	13.5	9.6	98.13
1.0	7	43.5	13.5	17.2	97.98
2.0	3	30.5	26.5	17.2	97.85
3.0	3	30.5	26.5	17.2	97.85
4.0	3	31.0	26.5	15.9	97.74
5.0	3	31.0	26.5	15.9	97.74
6.0	3	30.5	27.0	12.6	97.49
7.0	3	30.5	27.0	12.6	97.49
8.0	1	0.0	27.0	12.6	97.31

Table B.9: Hard Handover Using Pilot Reference: Street Canyon Environment

Threshold Δ_{Thresh} (dB)	No. Handover Attempts	Total Distance (m)	First Handover @ (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0	17	43.5	13.5	9.6	98.17
1	11	43.5	13.5	13.1	98.15
2	9	34.5	22.5	13.1	98.08
3	7	34.5	22.5	15.9	97.90
4	3	30.5	26.5	17.2	97.85
5	3	31.0	26.5	15.9	97.74
6	3	31.0	26.5	15.9	97.74
7	3	31.0	26.5	15.9	97.74
8	3	31.0	26.5	15.9	97.74

Table B.10: Hard Handover Using SINR Reference: Street Canyon Environment

Threshold Δ_{Thresh} (dB)	Timer 1 t_{Drop} (s)	Timer 2 t_{Add} (s)	Handover Start (m)	Handover Region (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	1.70	0.00	13.5	57.0	22.7	99.97
	0.05	0.05	27.0	0.0	12.6	97.31
	1.65	1.65	43.5	0.0	7.4	87.91
1.0	1.40	0.00	13.5	57.0	22.7	99.97
	0.10	0.10	27.5	0.0	12.6	96.89
	1.65	1.65	43.5	27.0	7.4	89.33
2.0	1.05	0.00	13.5	57.0	22.7	99.97
	0.20	0.20	28.5	3.0	12.6	96.66
	2.90	2.90	56.0	14.5	7.4	84.67
3.0	0.90	0.00	13.5	57.0	22.7	99.97
	0.20	0.20	28.5	4.0	12.6	96.71
	2.90	2.90	56.0	14.5	7.4	84.67
4.0	0.70	0.00	13.5	57.0	17.7	99.97
	0.20	0.20	28.5	6.0	12.6	97.71
	2.90	2.90	56.0	14.5	7.4	84.67
5.0	0.85	0.00	4.5	66.0	24.6	99.99
	0.20	0.20	25.5	9.0	17.8	97.71
	2.90	2.90	56.0	14.5	7.4	84.67
6.0	0.85	0.00	4.0	66.5	24.6	100.00
	0.30	0.30	29.5	6.0	12.6	96.52
	2.90	2.90	56.0	14.5	7.4	84.67
7.0	0.85	0.00	4.0	66.5	24.6	100.00
	0.30	0.30	24.5	11.0	17.8	97.96
	2.90	2.90	56.0	14.5	7.4	84.67
8.0	0.85	0.00	4.0	66.5	24.6	100.00
	0.45	0.45	31.0	6.0	12.6	96.01
	3.60	3.60	63.0	7.5	7.4	81.19

Table B.11: Optimised Soft Handover Using Pilot Reference: Street Canyon Environment

Threshold Δ_{Thresh} (dB)	Timer 1 t_{Drop} (s)	Timer 2 t_{Add} (s)	Handover Start (m)	Handover Region (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	1.70	0.00	13.5	57.0	22.7	99.97
	0.10	0.10	27.5	0.0	12.6	96.89
	1.65	1.65	43.5	0.0	7.4	87.91
1.0	1.70	0.00	13.5	57.0	22.7	99.97
	0.10	0.10	27.5	0.0	12.6	96.89
	1.65	1.65	43.5	0.0	7.4	87.91
2.0	1.15	0.00	13.5	57.0	22.7	99.97
	0.10	0.10	27.5	0.0	12.6	96.89
	1.65	1.65	43.5	27.0	7.4	89.33
3.0	0.95	0.00	13.5	57.0	22.7	99.97
	0.20	0.20	28.5	4.0	12.6	96.71
	1.65	1.65	43.5	27.0	7.4	89.33
4.0	0.95	0.00	13.5	57.0	22.7	99.97
	0.20	0.20	28.5	4.0	12.6	96.71
	2.90	2.90	56.0	14.5	7.4	84.67
5.0	0.70	0.00	13.5	56.0	22.7	99.97
	0.20	0.20	28.5	6.0	12.6	96.71
	2.90	2.90	56.0	14.5	7.4	84.67
6.0	0.70	0.00	13.5	56.0	22.7	99.97
	0.20	0.20	28.5	6.0	12.6	96.71
	2.90	2.90	56.0	14.5	7.4	84.67
7.0	0.70	0.00	13.5	56.0	22.7	99.97
	0.20	0.20	28.5	6.0	12.6	96.71
	2.90	2.90	56.0	14.5	7.4	84.67
8.0	0.70	0.00	13.5	57.0	22.7	99.97
	0.20	0.20	28.5	6.0	12.6	96.71
	2.90	2.90	56.0	14.5	7.4	84.76

Table B.12: Optimised Soft Handover Using SINR Reference: Street Canyon Environment

Appendix C

Optimised Handover Results from Macrocell-Microcell Field Trials

C.1 Macrocell-Microcell Handover: Study Case I

Threshold Δ_{Thresh} (dB)	No. Handover Attempts	Total Distance (m)	First Handover @ (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	5	21.5	44.0	8.2	99.67
1.0	3	12.0	44.0	8.2	99.66
2.0	3	12.0	44.0	8.2	99.66
3.0	3	12.5	44.0	8.2	99.61
4.0	3	12.5	44.0	8.2	99.61
5.0	3	12.5	44.0	8.2	99.61
6.0	1	0.0	57.0	7.0	99.43
7.0	1	0.0	57.0	7.0	99.43
8.0	1	0.0	57.0	7.0	99.43

Table C.1: Hard Handover Using Pilot Reference: Macro-Microcell Study Case I

Threshold Δ_{Thresh} (dB)	No. Handover Attempts	Total Distance (m)	First Handover @ (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	5	21.5	44.0	8.2	96.67
1.0	3	12.0	44.0	8.2	96.66
2.0	3	12.0	44.0	8.2	96.66
3.0	3	12.0	44.0	8.2	96.66
4.0	3	12.5	44.0	8.2	96.61
5.0	3	12.5	44.0	8.2	96.61
6.0	3	12.5	44.0	8.2	96.61
7.0	1	0.0	56.5	13.3	96.54
8.0	1	0.0	56.5	13.3	96.54

Table C.2: Hard Handover Using SINR Reference: Macro-Microcell Study Case I

Threshold Δ_{Thresh} (dB)	Timer 1 t_{Drop} (s)	Timer 2 t_{Add} (s)	Handover Start (m)	Handover Region (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	1.15	0.00	44.0	33.0	13.3	99.95
	0.05	0.05	56.5	0.0	13.3	99.54
	0.30	0.30	59.0	0.0	7.0	98.59
1.0	0.90	0.00	43.5	31.0	14.5	99.96
	0.10	0.10	57.0	0.0	7.0	99.43
	0.30	0.30	59.0	0.0	7.0	98.59
2.0	0.90	0.00	43.5	32.0	14.5	99.96
	0.15	0.15	57.5	0.0	7.0	99.20
	0.30	0.30	59.0	0.0	7.0	98.59
3.0	0.50	0.00	43.5	28.0	14.5	99.96
	0.15	0.15	57.5	0.5	7.0	99.20
	0.30	0.30	59.0	0.0	7.0	98.59
4.0	0.50	0.00	43.5	29.5	14.5	99.96
	0.15	0.15	57.5	0.5	7.0	99.20
	0.30	0.30	59.0	0.0	7.0	98.59
5.0	0.50	0.00	43.5	29.5	14.5	95.96
	0.20	0.20	57.5	1.0	7.0	99.20
	0.35	0.35	59.0	1.0	7.0	98.59
6.0	0.45	0.00	41.5	31.0	14.5	99.97
	0.25	0.25	58.0	1.5	7.0	99.02
	0.35	0.35	59.0	1.5	7.0	98.59
7.0	0.45	0.00	41.0	31.0	14.5	99.97
	0.25	0.25	58.0	1.5	7.0	99.02
	0.35	0.35	59.0	1.5	7.0	98.59
8.0	0.45	0.00	41.5	34.5	14.5	99.98
	0.25	0.25	58.0	1.5	7.0	99.02
	0.35	0.35	59.0	1.5	7.0	98.59

Table C.3: Optimised Soft Handover Using Pilot Reference: Macro-Microcell Study Case I

Threshold Δ_{Thresh} (dB)	Timer 1 t_{Drop} (s)	Timer 2 t_{Add} (s)	Handover Start (m)	Handover Region (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	1.15	0.00	44.0	33.0	13.3	99.95
	0.05	0.05	56.5	0.0	13.3	99.54
	0.30	0.30	59.0	0.0	7.0	98.59
1.0	1.15	0.00	44.0	34.0	13.3	99.95
	0.05	0.05	56.5	0.0	13.3	99.54
	0.30	0.30	59.0	0.0	7.0	98.59
2.0	1.15	0.00	44.0	34.0	13.3	99.95
	0.05	0.05	56.5	0.0	13.3	99.54
	0.30	0.30	59.0	0.0	7.0	98.59
3.0	1.15	0.00	44.0	34.0	13.3	99.95
	0.15	0.15	57.5	0.0	7.0	99.20
	0.30	0.30	59.0	0.0	7.0	98.59
4.0	1.15	0.00	43.5	34.5	14.5	99.96
	0.15	0.15	57.5	0.5	7.0	99.20
	0.30	0.30	59.0	0.0	7.0	98.59
5.0	0.85	0.00	43.5	31.5	14.5	99.96
	0.15	0.15	57.5	0.5	7.0	99.20
	0.30	0.30	59.0	0.0	7.0	98.59
6.0	0.80	0.00	43.5	31.5	14.5	99.56
	0.25	0.25	58.5	0.5	7.0	98.84
	0.30	0.30	59.0	0.0	7.0	98.59
7.0	0.60	0.00	43.5	29.5	14.5	99.96
	0.25	0.25	58.5	0.5	7.0	98.84
	0.30	0.30	59.0	0.0	7.0	98.59
8.0	0.55	0.00	43.5	29.0	14.5	99.96
	0.25	0.25	58.0	1.0	7.0	99.02
	0.30	0.30	59.0	0.0	7.0	98.59

Table C.4: Optimised Soft Handover Using SINR Reference: Macro-Microcell Study Case I

C.2 Macrocell-to-Microcell Handover: Study Case II

Threshold Δ_{Thresh} (dB)	No. Handover Attempts	Total Distance (m)	First Handover @ (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	1	0.0	52.0	9.8	99.81
1.0	1	0.0	52.0	9.8	99.81
2.0	1	0.0	52.0	9.8	99.81
3.0	1	0.0	52.0	9.8	99.81
4.0	1	0.0	52.0	9.8	99.81
5.0	1	0.0	52.0	9.8	99.81
6.0	1	0.0	53.0	9.8	99.63
7.0	1	0.0	53.0	9.8	99.63
8.0	1	0.0	53.0	9.8	99.63

Table C.5: Hard Handover Using Pilot Reference: Macro-Microcell Study Case II

Threshold Δ_{Thresh} (dB)	No. Handover Attempts	Total Distance (m)	First Handover @ (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	1	0.0	52.0	9.8	99.81
1.0	1	0.0	52.0	9.8	99.81
2.0	1	0.0	52.0	9.8	99.81
3.0	1	0.0	52.0	9.8	99.81
4.0	1	0.0	52.0	9.8	99.81
5.0	1	0.0	52.0	9.8	99.81
6.0	1	0.0	52.0	9.8	99.81
7.0	1	0.0	52.0	9.8	99.81
8.0	1	0.0	52.0	9.8	99.81

Table C.6: Hard Handover Using SINR Reference: Macro-Microcell Study Case II

Threshold Δ_{Thresh} (dB)	Timer 1 t_{Drop} (s)	Timer 2 t_{Add} (s)	Handover Start (m)	Handover Region (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	0.00	0.00	52.0	0.0	9.8	99.81
	0.00	0.00	52.0	0.0	9.8	99.81
	0.10	0.10	53.0	0.0	9.8	99.63
1.0	0.00	0.00	52.0	0.0	9.8	99.81
	0.00	0.00	52.0	0.0	9.8	99.81
	0.10	0.10	53.0	0.0	9.8	99.63
2.0	0.00	0.00	51.5	0.5	13.9	99.84
	0.00	0.00	51.5	0.5	13.9	99.84
	0.15	0.15	53.0	0.5	9.8	99.63
3.0	0.00	0.00	51.5	0.5	13.9	99.84
	0.00	0.00	51.5	0.5	13.9	99.84
	0.15	0.15	53.0	0.5	9.8	99.63
4.0	0.05	0.00	51.0	2.5	13.9	99.88
	0.05	0.00	51.0	2.5	13.9	99.88
	0.20	0.20	53.0	2.0	9.8	99.64
5.0	0.20	0.00	51.0	6.5	13.9	99.92
	0.05	0.05	51.5	2.0	13.9	99.87
	0.20	0.20	53.0	4.5	9.8	99.68
6.0	0.25	0.00	46.5	12.5	13.9	99.95
	0.05	0.05	51.5	2.0	13.9	99.87
	0.20	0.20	53.0	5.5	9.8	99.68
7.0	0.25	0.00	43.0	16.0	13.9	99.96
	0.10	0.10	52.0	2.0	9.8	99.83
	0.20	0.20	53.0	5.5	9.8	99.68
8.0	0.45	0.00	38.0	23.0	13.9	99.97
	0.10	0.10	52.0	2.0	9.8	99.83
	0.20	0.20	53.0	5.5	9.8	99.68

Table C.7: Optimised Soft Handover Using Pilot Reference: Macro-Microcell Study Case II

Threshold Δ_{Thresh} (dB)	Timer 1 t_{Drop} (s)	Timer 2 t_{Add} (s)	Handover Start (m)	Handover Region (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	0.00	0.00	52.0	0.0	9.8	99.81
	0.00	0.00	52.0	0.0	9.8	99.81
	0.10	0.10	53.0	0.0	9.8	99.63
1.0	0.00	0.00	51.5	0.5	13.9	99.84
	0.00	0.00	51.5	0.5	13.9	99.84
	0.15	0.15	53.0	0.5	9.8	99.63
2.0	0.00	0.00	51.5	0.5	13.9	99.84
	0.00	0.00	51.5	0.5	13.9	99.84
	0.15	0.15	53.0	0.5	9.8	99.63
3.0	0.00	0.00	51.5	0.5	13.9	99.84
	0.00	0.00	51.5	0.5	13.9	99.84
	0.15	0.15	53.0	0.5	9.8	99.63
4.0	0.00	0.00	51.5	0.5	13.9	99.84
	0.00	0.00	51.5	0.5	13.9	99.84
	0.15	0.15	53.0	0.5	9.8	99.63
5.0	0.30	0.00	51.5	7.0	13.9	99.92
	0.05	0.05	52.0	0.5	9.8	99.81
	0.15	0.15	53.0	0.5	9.8	99.63
6.0	0.20	0.00	51.5	6.0	13.9	99.91
	0.05	0.05	52.0	1.5	9.8	99.83
	0.15	0.15	53.0	1.5	9.8	99.64
7.0	0.20	0.00	51.0	7.5	13.9	99.93
	0.05	0.05	51.5	2.0	13.9	99.87
	0.20	0.20	53.0	5.5	9.8	99.68
8.0	0.20	0.00	51.0	7.5	13.9	99.93
	0.05	0.05	51.5	2.0	13.9	99.87
	0.20	0.20	53.0	5.5	9.8	99.68

Table C.8: Optimised Soft Handover Using SINR Reference: Macro-Microcell Study Case II

C.3 Macrocell-to-Microcell Handover: Study Case III

Reference Signal	Threshold Δ_{Thresh} (dB)
Pilot	11.0dB
SINR	17.0dB

Table C.9: Minimum Threshold to Prevent Hard Handover: Macrocell-Microcell Study Case III

Threshold Threshold Δ_{Thresh}(dB)	Timers for Pilot Reference $t_{Add} = t_{Drop}$ (s)	Timers for SINR Reference $t_{Add} = t_{Drop}$ (s)
0.0	0.4	0.35
1.0	0.4	0.35
2.0	0.4	0.35
3.0	0.6	0.40
4.0	0.6	0.40
5.0	0.6	0.60
6.0	0.6	0.60
7.0	0.6	0.60
8.0	0.6	0.60

Table C.10: Handover Threshold and Minimum Timer Value to Prevent Soft Handover: Macrocell-Microcell Study Case III

Threshold Δ_{Thresh} (dB)	No. Handover Attempts	Total Distance (m)	First Handover @ (m)	$SINR_{min}$ (dB)	Cumulative Power (%)
0.0	0.40	1	60.0	0.0	1.3
1.0	0.40	1	60.0	0.0	1.3
2.0	0.40	1	60.0	0.0	1.3
3.0	0.60	1	62.0	10.5	1.3
4.0	0.60	1	52.0	12.0	1.3
5.0	0.60	1	61.5	12.5	1.3
6.0	0.60	1	61.5	12.5	1.3
7.0	0.60	1	61.5	12.5	1.3
8.0	0.60	1	61.5	16.0	1.3

Table C.11: Soft Handover using Pilot Reference: Study Case I using Study Case III Timer Settings

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